METHODS AND APPARATUS FOR DETERMINING FOCUS

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of prior application US Provisional Application No. 61/864,527, filed 10 August 2013 by Stilian Ivanov Pandev, which application is herein incorporated by reference in its entirety for all purposes.

TECHNICAL FIELD OF THE INVENTION

[0002] The present invention relates generally to methods and systems for determination of photolithography parameters and, more specifically, to determination of focus parameters using focus exposure matrix (FEM) wafers.

BACKGROUND

[0003] Photolithography or optical lithography systems used in the manufacture of integrated circuits have been around for some time. Such systems have proven extremely effective in the precise manufacturing and formation of very small details in the product. In most photolithography systems, a circuit image is written on a substrate by transferring a pattern via a light or radiation beam (e.g., UV or ultraviolet light). For example, the lithography system may include a light or radiation source that projects a circuit image through a reticle and onto a silicon wafer coated with a material sensitive to irradiation, *e.g.*, photoresist. The exposed photoresist typically forms a pattern that after development masks the layers of the wafer during subsequent processing steps, as for example deposition and/or etching.

[0004] Two example process parameters for controlling the photolithographic process are focus and exposure (also referred to as "dose"). Focus generally deals with clarity with which an optical subsystem of the lithography system renders an image, and exposure generally deals with the amount or dosage of light (or radiation) that is used to form the pattern (such as the light produced by a light

source of the lithography system). Both affect the circuit pattern in a non-trivial way. For example, changes in focus and exposure may cause changes in the resist profile and the shape of the circuit printed in the photoresist.

[0005] Different structure types often have different process windows for controlling lithography focus and exposure settings at which such structures can be formed without defects. The intersection of these windows for the different structures can be defined as an optimal range of focus and exposure settings or window.

[0006] Presently, optimal focus and exposure settings of the lithography system are determined using a focus exposure matrix (FEM) to expose a wafer with multiple combinations of focus and exposure and then inspecting the resultant pattern for the best resist profiles - the resist profiles that more closely match the desired or optimal resist profiles. The inspection is generally performed by a CD scanning electron microscope (CD-SEM) that measures various parameters of the resist profile, such as CD. In most cases, the wafer has to be destroyed, *e.g.,* cut through, so that these parameters can be measured. The process window is generally defined as the region of focus and exposure that keeps the final resist profile within prescribed specifications (e.g., process window typically includes the optimum focus and exposure). However, CD-SEM techniques for determining an optimum process window are often time consuming, unreliable, and unable to measure certain a sidewall resist profile.

[0007] Additionally, as IC structure size continues to shrink and the process window margins also shrink, it becomes challenging to maintain structure uniformity during production. Several factors in manufacturing, including lithography cell exposure sequence perturbations convoluted with reticle enhancement features, contribute to feature response that varies across the exposure field in unexpected and often unpredictable ways.

[0008] In view of the foregoing, improved techniques for determining and monitoring optimal focus and exposure settings of a photolithographic system are desired.

SUMMARY

[0009] The following presents a simplified summary of the disclosure in order to provide a basic understanding of certain embodiments of the invention. This summary is not an extensive overview of the disclosure and it does not identify key/critical elements of the invention or delineate the scope of the invention. Its sole purpose is to present some concepts disclosed herein in a simplified form as a prelude to the more detailed description that is presented later.

[0010] In one embodiment, a method of determining optimal focus for a photolithography system is disclosed. A plurality of optical signals are acquired from a particular target located in a plurality of fields on a semiconductor wafer, and the fields were formed using different process parameters, including different focus values. A feature is extracted from the optical signals related to changes in focus. A symmetric curve is fitted to the extracted feature of the optical signals as a function of focus. An extreme point in the symmetric curve is determined and reported as an optimal focus for use in the photolithography system.

[0011] In a specific implementation, the extracted feature is a combination of one or more of the optical signals that is most sensitive to changes in focus, as compared to other combinations of one or more of the optical signals. In another aspect, the extracted feature is a linear combination of the optical signals. In another embodiment, the extracted feature is a non-linear combination of the optical signals. In yet another aspect, the extracted feature is a plurality of second optical signals that are created from a transformation of the first optical signals. In a further aspect, the transformation is accomplished using a principal component analysis (PCA), Independent Component Analysis (ICA), or Local Linear Embedding (LLE) algorithm. In yet a further aspect, the transformation is accomplished using a principal component analysis (PCA) and the extracted feature is the second optical signals with respect to a first principal component resulting from the PCA transformation.

[0012] In other embodiments, the optical signals are acquired from a focus-exposure matrix (FEM) wafer. In another aspect, the symmetric curve fitted to the extracted feature is a parabola. In a further aspect, the method includes repeating the operations for acquiring, extracting, fitting, and determining and reporting for a plurality of wafers to determine a plurality of optimal focus and determining a relationship between an actual focus of the photolithography system and an optimal focus.

[0013] In another embodiment, the optical signals are acquired using one or more of the following: spectroscopic ellipsometry, Mueller matrix spectroscopic ellipsometry, spectroscopic reflectometry, spectroscopic scatterometry, beam profile reflectometry, beam profile ellipsometry, a single wavelength, a single discrete wavelength range, or multiple discrete wavelength ranges.

[0014] In an alternative embodiment, the invention pertains to a system for inspecting or measuring a specimen. This system comprises an illuminator for generating illumination and illumination optics for directing the illumination towards a particular target located in a plurality of fields on a semiconductor wafer. The fields were formed using different process parameters, including different focus values. The system also includes collection optics for directing a plurality of optical signals from the particular target located in the plurality of fields in response to the illumination to a detector system and the detector sensor for acquiring the plurality of optical signals from the particular target from the plurality of fields in response to the illumination. The system further includes a processor and memory configured for performing any of the above described operations. In a specific implementation, the system is in the form of an elipsometer and includes a polarization state generator for producing a polarized state in the illumination and a polarization state analyzer for analyzing a polarized state of the optical signals. In other embodiments, the system is in the form of a spectroscopic ellipsometer, Mueller matrix spectroscopic ellipsometer, spectroscopic reflectometer, spectroscopic scatterometer, beam profile reflectometer, or beam profile ellipsometer.

[0015] These and other aspects of the invention are described further below with reference to the figures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0016] Figure 1 illustrates an example Bossung Plot for CD as a function of focus for varying values of exposure.

[0017] Figure 2 illustrates a second example of a Bossung Plot for exposure vs. focus for varying values of CD.

[0018] Figure 3 is a flow chart illustrating a technique for determining optimal focus in accordance with one embodiment of the present invention.

[0019] Figure 4A is a plot of a simplified focus and dose dataset as a function of three signal combinations in accordance with one embodiment of the present invention.

[0020] Figure 4B illustrates the three eigenvectors for the three dimensional dataset of Figure 4A in accordance with a specific implementation of the present invention.

[0021] Figure 5A is a first example Bossung Plot of a set of optical signals' first principal component (PC1) as a function of focus and varying exposure in accordance with one embodiment of the present invention.

[0022] Figure 5B includes a second example of the optical signals' PC1 mapped as a set of wafer contour areas as a function of focus and varying exposure in accordance with another embodiment of the present invention.

[0023] Figure 5C is a Bossung Plot of the first principal component (PC1) for a set of CD values, which are simulated from the same FEM reticle structures that are used to fabricate the FEM wafer targets of Figures 5A and 5B.

[0024] Figure 5D includes wafer map of a set of CD values transformed to their first principal component PC1 and arranged as a set of contour areas as a function of focus and varying exposure.

[0025] Figure 6 is an example relationship between optimal focus and programmed focus in accordance with an alternative embodiment of the present invention.

[0026] Figure 7 illustrates a system for determining optimal focus in accordance with one embodiment of the present invention.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

[0027] In the following description, numerous specific details are set forth in order to provide a thorough understanding of the present invention. The present invention may be practiced without some or all of these specific details. In other instances, well known process operations have not been described in detail to not unnecessarily obscure the present invention. While the invention will be described in conjunction with the specific embodiments, it will be understood that it is not intended to limit the invention to the embodiments.

[0028] Introduction

[0029] A focus-exposure matrix obtained from a FEM wafer, by way of example, may be visualized using a Bossung Plot to facilitate determination of a lithography process window. The Bossung Plot generally plots CD vs. focus position for varying levels of exposure, such as the example in Figure 1. As shown, varying levels of exposure are plotted as contour lines with CD representing the Y axis and focus position representing the X axis of the graph. A depth of focus (DOF) value of zero corresponds to a plane of focus at the top of the resist, while negative or positive DOF values result in plane of focus that is at a lower or higher level, respectively, with respect to the resist surface.

[0030] The process window is generally defined as the region of focus and exposure (*e.g.*, 112) that keeps the final resist profile within predefined specifications. For instance, CD remains at a stable range of acceptable values (or predefined CD limits) for a specific range of DOF values and exposure doses. CD changes drastically (*e.g.*, increases or decreases for particular exposure curves) for focus ranges 116a and 116b. An optimum focus 114 can be defined as the center of

symmetry (COS) of the process window 112 for a tolerable range of exposures or dose settings.

[0031] Alternatively, the Bossung Plot may plot exposure vs. focus for varying values of CD, *e.g.,* the values of CD are plotted as contour lines with exposure representing the Y axis and focus position representing the X axis of the graph as shown in Figure 2. The overlapped Bossung Plots include a first Bossung Plot 262 and a second Bossung Plot 264. The overlapped Bossung plots each include three contours 265a~c of different constant line heights and three contours 263a~c of different constant line widths for a line space grating. Each curve represents either a line width or height. For instance, the three line width curves 263a~c correspond to constant line widths 120 nm, 123 nm, and 126 nm, respectively, and the three height curves 265a~c correspond to constant heights 284 nm, 290 nm, and 296 nm, respectively. As shown, a pair of specific contours of line height and line width intersects at only one focus-exposure combination, demonstrating a unique simultaneous solution for both focus and exposure. If the line width was determined to be 123 nm (curve 263b), and the height was determined to be 284 nm (curve 265a), then the optimal exposure would be approximately equal to 26 units and the optimal focus would be approximately equal to 0.2 um.

[0032] Other resist profile parameters, for example, sidewall angle may also be visualized using Bossung Plots. These plots are generally harder to obtain since measuring these shapes is often a difficult endeavor. In most cases, the wafer has to be destroyed, *e.g.,* cut through, so that these parameters can be measured.

[0033] It has been found that optical signals obtained from an FEM wafer can also be visualized in a Bossung Plot and the resulting curves can have a similarly shape as the curves in a corresponding CD Bossung Plot. Additionally, the optical signals can be used as a proxy for CD in a technique for determining optimal lithography settings, as well as process monitoring and process control applications. In one example implementation, a COS of a combination of one or more optical signals is used to determine optimal focus.

[0034] Determining Lithography Process Parameters Using Optical Signals:

[0035] Figure 3 is a flow chart illustrating a technique 300 for determining an optimal focus in accordance with one embodiment of the present invention. Initially, a plurality of optical signals may be obtained from a particular target from different fields formed with different process parameters, including focus, in operation 302. For example, different types of optical signals, such as a plurality of different wavelengths, polarizations, etc., can be acquired from a specific target, at different focus-exposure positions on an FEM wafer, using an optical metrology tool. Since a particular target from different FEM fields is exposed to different conditions, this target will tend to have a different structure in at least some of the different fields.

[0036] In more general embodiments, process parameter variations are organized in a Design of Experiments (DOE) pattern on the surface of a semiconductor wafer (referred to as a DOE wafer). In this manner, the optical signal acquisition sites correspond to different locations on the wafer surface having different associated process parameter values. In one example, the DOE pattern is a Focus/Exposure Matrix (FEM) pattern. Typically, a DOE wafer exhibiting a FEM pattern includes a grid pattern of measurement sites. In one grid direction (e.g., the x-direction), the exposure dosage is varied while the depth of focus is held constant. In the orthogonal grid direction (e.g., the y-direction), the depth of focus is varied while the exposure dosage is held constant. In this manner, measurement data collected from the FEM wafer includes data associated with known variations in the focus and dosage process parameters. In the illustrated example, the optical signal data is acquired from a FEM wafer that processed with known variations in focus and exposure. However, in general, optical signal data associated with known variation of any set of process parameters, structural parameters, or both, are contemplated.

[0037] Several embodiments of targets, their fabrication, and their arrangements with respect to measurement sites and fields are described further in U.S. Patent 7,382,447 by Walter Mieher et al. and issued 3 June 2008, which patent is incorporated herein by reference in its entirety. In general, printing of FEM targets may be accomplished in a layer of photoresist by projecting light or radiation

through a pattern of a test reticle. The targets may be printed using a different combination of process parameters (test matrix).

[0038]). The printed targets may be printed in a variety of different wafer layers. In particular, the printed targets are generally printed in a layer of photoresist using standard lithography processes (e.g., projecting a circuit image through a reticle and onto a silicon wafer coated with photoresist). The wafer may be a test wafer with layers of materials that correspond to the materials typically present on product wafers at that step in the test process. The printed targets may be printed over other targets in underlying layers. The wafer may be a product wafer that has the potential to produce working devices. The wafer may be a simple test wafer only used for testing the lithography system. When using multiple test wafers, the same or different test reticles may be used. The different test reticles may have patterns with different dimensions so as to produce a wider range of test data.

[0039] The process parameters used to form the printed targets are generally configured to keep the target characteristics within desired specifications. The printed targets may be printed on a test wafer as a part of a test procedure or they may be printed on a production wafer during production. In production, the printed targets are typically printed in the scribe line between device areas (e.g., dies that define the IC) disposed on a production wafer. The measurement sites may be dedicated targets disposed around the device structures or they may be a portion of the device structure (e.g., a periodic portion). As should be appreciated, using a portion of the device structure may be more difficult, but it tends to be more accurate since it is a portion of the device structure. In another embodiment, the printed targets may be printed across the entire test wafer.

[0040] The FEM measurement sites are generally located across the focus exposure matrix wafer. In fact, there may generally be one or more measurement sites per field. Each field may be formed using a different combination of focus and exposure (or may be focus or exposure only). For example, a first field may be produced using a first combination, and a second field may be produced using a second combination that is different than the first combination. The multiple combinations

can be produced using varying focus and varying exposure, varying focus – constant exposure, constant focus – varying exposure, and the like.

[0041] The number of measurement sites may also differ. The number of sites per field is generally smaller on production wafers since the real estate on production wafers is so valuable. Also, fewer measurements are made on a product wafer than on a focus exposure matrix wafer due to time constraints in production. In one embodiment, a single site is measured per field. In another embodiment, multiple sites are measured per field.

[0042] In most cases, the measurement site targets are formed from identically designed patterns using different processing parameters. It should be noted, however, that different focus exposure matrices may have different targets. For example, a first test matrix may be performed using a first grating type and a second test matrix may be performed using a second grating type that is different than the first grating type.

[0043] The targets may widely vary. The target structure may be in the form of a grating that is typically periodic. The grating may be periodic in one direction (X or Y) as, for example, a line space grating, or it may be periodic in two directions (X and Y) as, for example, a grid space grating. Examples of a grid space grating may include an array of lines in the Y direction with each line being segmented in the X direction. Another grid space example is an array of dot structures. That is, the targets may take the form of a line space grating, grid space grating, checkerboard pattern target, etc. *The target design characteristics may each include line width (width at a specific height), line space width, line length, shape, side wall angle, height, pitch, grating orientation, top-profile (degree of top rounding or T topping), bottom profile (footing), etc.

[0044] When using multiple printed targets, each may have the same or different characteristics. As should be appreciated, different target characteristics, such as different shapes and pitch, exhibit different response to focus and, therefore, it may be advantageous to measure distinct measurement sites having different characteristics.

[0045] The optical signals acquired from the target sites may include any type of signals that have been found to correlate to target parameters, such as CD, sidewall, and height, and also changes in process. For example, scatterometry measurements may contain such information. Example signals include, but are not limited to, any type of spectroscopic ellipsometry or reflectometry signals, including: Ψ, Δ, Rs (complex reflectivity of the s polarization), Rp (complex reflectivity of the p polarization), Rs ($|r_s|^2$), Rp ($|r_p|^2$), R (unpolarized reflectivity), α (spectroscopic "alpha" signal), β (spectroscopic "beta" signal), and functions of these parameters, such as $\tan(\Psi)$, $\cos(\Delta)$, $((Rs-Rp)/(Rs+Rp))$, etc. The signals could alternatively or additionally be measured as a function of incidence angle, detection angle, polarization, azimuthal angle of incidence, detection azimuthal angle, angular distribution, phase, or wavelength or a combination of more than one of these parameters. The signals could also be a characterization of a combination of signals, such as an average value of a plurality of any of the above described ellipsometry and/or reflectometry signal types. The signals may alternatively take the form of images or, rather, a characteristic of such images, such as an intensity value or a combination (*e.g.,* average or addition) of intensity values. Other embodiments may use monochromatic or laser light sources where at least one of the signals may be obtained at a single wavelength, instead of multiple wavelengths.

[0046] Scatterometry is a measurement technique that generates optical signals that are dependent on various types of target parameters, such as CD. The target is typically in the form of grating structure, such as a periodic grating structure. In scatterometry, one or more light or radiation beams are made incident on the grating structure and the scattered, reflected and/or diffracted beams emanating from the grating structure are measured. The incident light may be directed toward the target normally or at some angle to the normal. The light emanating from the grating structure is typically scattered, reflected and/or diffracted at various orders, i.e., angles relative to the incident light. The characteristics of the scattered, reflected and/or diffracted light (e.g., intensity, phase, polarization, and the like) at the various orders is measured thereby forming a measurement signal or measured spectra. The characteristics of the scattered, reflected and/or diffracted light

generally pertain to information about characteristics of the grating structure. That is, the scattered, reflected and/or diffracted light typically changes in accordance with the shape of the structures and, thus, there is a unique relationship between the measured spectra and the profile of a grating structure and the processed used to fabricate such structure.

[0047] The metrology tool can comprise one or more hardware configurations which may be used in conjunction with certain embodiments of this invention to, e.g., measure the various aforementioned optical signals from FEM sites. Examples of such hardware configurations include, but are not limited to, the following: spectroscopic ellipsometer (SE), SE with multiple angles of illumination, SE measuring Mueller matrix elements (e.g. using rotating compensator(s)), single-wavelength ellipsometers, beam profile ellipsometer (angle-resolved ellipsometer), beam profile reflectometer (angle-resolved reflectometer), broadband reflective spectrometer (spectroscopic reflectometer), single-wavelength reflectometer, angle-resolved reflectometer, imaging system, scatterometer (e.g. speckle analyzer), etc. As should be appreciated, optical metrology, such as scatterometry, is one of the few types of metrology that has true in-situ potential for controlling focus and or exposure during a production run, *e.g.*, optical metrology is suitable for die to die, wafer to wafer, run to run monitoring (and the like). The hardware configurations can also generally be separated into discrete operational systems. On the other hand, one or more hardware configurations can be combined into a single tool.

[0048] Referring back to the illustrated technique, a feature related to changes in the focus, as well as changes in other process parameters, may then be extracted from the optical signals in operation 304. In one embodiment, a combination of one or more of the acquired signals that is most sensitive to focus and dose change is extracted. For example, a single signal type, combination of signal types (such as a set of different wavelength ranges), may be extracted as providing more information related to focus and dosage change. In other embodiments, a linear combination, nonlinear combination, or weighted combination of one or more signals may be extracted as the feature from the optical signals.

[0049] Any suitable feature extraction technique may be implemented so as to extract a feature from one or more of the optical signals with the best information pertaining to changes in process parameters, such as focus/dose. An operator of the metrology tool may select the feature to be extracted by assessing different signal or signal property combinations through trial and error to determine a best feature that provides a change trajectory with respect to the focus that is similar to a change trajectory in a characteristic of the fabricated structure as a function of focus. An automated analysis of different signals or signal combinations may be executed based on optimization of some criteria, such as selecting the signal or signal combination that forms a set of parabolic shapes (for the different exposures) as a function of focus with minimum noise. Additionally, a combination of wavelength ranges may be selected so as to cancel any effects to the signal caused by targets in lower layers. For instance, certain wavelengths may result in a circular contour pattern with respect to the focus and dose wafer sites, as opposed to parabolic shaped contours for wavelengths that are insensitive to underlying structures. The wavelength ranges that are found to be sensitive to underlying layer targets may be deselected from being used as an extracted feature.

[0050] Example automated feature extract techniques include Principal Component Analysis (PCA), Independent Component Analysis (ICA), Local Linear Embedding (LLE) algorithm, etc. Although the following example embodiments are described in terms of using the first principal component resulting from a PCA transformation in order to determine an optimal focus, other embodiments may utilize other feature extraction results or techniques. For instance, the first and second principal components as determined via PCA may be used. Any number of principal components may be selected based on the particular requirements of the application. In yet another example, the output from another feature extraction tool, such as ICA or LLE, may be used. Additionally, other process parameters, besides focus, may be optimized and monitored.

[0051] In a PCA embodiment, the extracted feature corresponds to a transformation of the signal dataset onto a different coordinate system and selection of a particular

dimension (or direction or projection direction) of such new coordinate system along which the transformed dataset has the most variation, which provides the most information with respect to process parameter changes. Said in another way, a dataset may be created with different combinations of one or more optical signals that can be defined as the variables (columns) for different focus/dose target sites or samples (rows). The first principal component corresponds to a transformed direction or dimension of the PCA-transformed dataset that is found to have the most variation. The second principal component has the second most variation, etc.

[0052] Figure 4A is a plot of a simplified focus and dose dataset as a function of three signal combinations in accordance with one embodiment of the present invention. As shown, the sample dataset has three dimensions corresponding to signals S1, S2, and S3. For instance, the dataset includes data points 402a and 402b that correspond to two different focus sites. As shown, signal S1 is a constant value for all the data points. That is, the data sets reside in a plane that is perpendicular to the S1 dimension.

[0053] Figure 4B illustrates the three eigenvectors for the three dimensional dataset of Figure 4A in accordance with a specific implementation of the present invention. As shown, the dataset has three eigenvectors ev1 (410a), e2 (410b), and e3 (410c). Each of the eigenvectors also has an eigenvalue that corresponds to the amount of variance in the dataset with respect to such eigenvector. For instance, the principal eigenvector e1 (410a) is associated with the most dataset variance. In contrast, the eigenvector e2 (410b) has significantly less dataset variance, and the eigenvector e3 (410c) has zero dataset variance.

[0054] Referring back to Figure 3, a symmetric curve can then be fitted to the extracted feature along the focus axis in operation 306. That is, any symmetric type of curve may be fit to the extracted feature data. In one specific example, a parabola is fitted to the extracted feature. The extreme point of the curve can then be determined and reported as the best focus in operation 308. For instance, the peak or valley of a fitted symmetric parabola can be defined as the optimal focus. The reported best focus may then be used to adjust or monitor the lithography

settings in operation 310. By way of specific examples, the determined optimal focus may be used to adjust or repair the stepper lens system, to choose optimum stepper operating parameters to minimize the negative impact of optical aberrations, or to monitor the stability of the stepper lens system. The optimal focus determination process 300 may then end.

[0055] The corrected focus exposure information may be input manually to the lithography tool by an operator or automatically by the system. In most cases, the corrections may be fed into a program or computer that analyzes and decides what actual correction to make. For example, the decision may be to not make a correction, *e.g.*, correction is too small. In addition, there may be other information from other processes that may alter the overall correction.

[0056] Turning back to a PCA example, the focus/dose dataset can be plotted with respect to the principal component. For instance, each sample data point can be plotted with the principal component direction being defined as the y axis and focus being defined as the x axis. The different doses can be represented as different contour lines. A symmetric parabola can then be fitted to this plotted dataset. Figure 5A includes a first example Bossung Plot 502 of a set of optical signals' first Principal Component (PC1) as a function of focus at varying exposure in accordance with one embodiment of the present invention. The PC1 of the optical signals may be analyzed to determine a curve fit, such as parabola 504 having a polynomial fit degree of 2. In the illustrated example, the fitted curve for PC1 is equal to $3.231847+2.9355253*\text{Focus}-211.48888*(\text{Focus}-0.04944)^2$. For this curve function, the minimum PC1 point corresponds to an optimal focus 506 of 0.0425.

[0057] Figure 5B includes a second example of the optical signals' PC1 that are mapped as a set of wafer contour areas as a function of focus and dose in accordance with another embodiment of the present invention. The contour areas correspond to different PC1 values that are calculated from the fitted curve function for particular sets of focus and exposure values. Different PC1 values can be given different colors and mapped to the corresponding FEM sites to form a PC1 wafer

map. These contours can also be analyzed to determine a maximum point of the contour curves that also corresponds to an optimal focus 512 of 0.0425.

[0058] Determining an optimal focus based on feature extraction with respect to optical signals appears to provide results that are consistent with applying feature extraction to CD values obtained from the same FEM sites. Figure 5C is a Bossung Plot 552 of the first principal component (PC1) for a set of CD values, which are simulated from the same FEM reticle structures that are used to fabricate the FEM wafer targets of Figures 5A and 5B. For a comparison of results, the CD values can be obtained via actual measurements on the FEM wafer targets or simulation. In the illustrated example, the fitted curve 554 for PC1 is equal to $0.8792593-0.6781819*focus-57.945882*(focus-0.04944)^2$. For this curve function, the maximum PC1 point corresponds to an optimal focus 556 of 0.0436. Likewise, Figure 5D includes a wafer map 560 of a set of CD values transformed to its first principal component PC1 arranged as a set of contour areas as a function of focus and dose. Accordingly, the CD Bossung Plots product substantially the same optimal focus 0.0436 (560) as the optical signals' principal component Bossung Plots of Figures 5A-B.

[0059] Certain techniques of the present invention provide an efficient, non-destructive way to determine optimal focus. Additionally, certain techniques for determining focus or other process parameters can be implemented without use of models.

[0060] The process for determining optimal focus can be applied to multiple target types (*e.g.*, repeating the process 300 of Figure 3 with a different particular target having different design characteristics, such as pitch, CD, etc.). Simultaneous solutions using multiple types of targets generally overcome problems associated with process parameter dependencies on target parameters that allow multiple solutions of the process parameters for a given target parameter value. For example, in the case of a particular line width, the focus exposure dependence is non-linear in focus and allows for multiple solutions for focus, even if the exposure dose is known accurately. Simultaneous solutions also can remove the degeneracy between

solutions that may be encountered when solving for focus and/or exposure with information from only one parameter (different target parameters may have different dependences on focus and exposure). Using focus solutions determined from many focus exposure matrix measurements can average out measurement errors, stepper errors, and the like.

[0061] Since each position in any particular exposure field of the lithography tool may also be associated with a slightly different tilt position (and corresponding focus offset position), a same target may be formed on multiple positons of each exposure field on the FEM wafer to determine an optimum focus for different field positions. An optimum focus for each field positon can then be determined based on the optical signals obtained from each field position from the multiple fields (e.g., exposed at different doses and different programmed focus). The optimum focus for each field position can then be used to program an optimum focus tilt for the entire exposure field to achieve different optimum focus values for different field positions.

[0062] Although an optimal or best focus can be determined, a lithography tool may actually program a different focus that may be caused by difficulties the tool has in sensing an accurate position of the wafer surface. That is, it may be difficult for the lithography tool to achieve a particular depth of focus with respect to the actual wafer surface. A particular optimum depth of focus with respect to a relatively transparent film, such as a photoresist material that is disposed over layers having other grating structures, is especially difficult to achieve. Consequently, the resulting programmed focus may not be equal to the input best or optimal focus.

[0063] Certain embodiments of the present invention may also provide ways to monitor the programmed focus. A relationship between the best and programmed focus can be determined ($focus_{best}=f(Focus_{programmed})$) based on the FEM dataset from multiple FEM wafers with programmed focus offsets. This relationship can be used as calibration for a model-less focus measurement. That is, the relationship can be used to adjust the focus. Figure 6 is an example relationship between optimal focus and programmed focus in accordance with an alternative embodiment of the present invention. Each point corresponds to a particular optimal or "predicted"

focus (determined from a particular set of FEM signals) and programmed "actual" focus.

[0064] By determining a relationship between the best and programmed focus, a separate model to derive the actual focus from geometric parameters (or optical signals) is not required. Because process variation is captured by this relationship, actual can be measured even when the underlying structure topology is changing due to process variations. This is impossible, or very difficult to model using existing model-based metrology methods. Traditionally, model-based semiconductor metrology includes formulating a metrology model that attempts to predict the measured optical signals based on a model of the interaction of the measurement target with the particular metrology system. The target-specific model includes a parameterization of the structure in terms of the physical properties of the measurement target of interest (e.g., film thicknesses, critical dimensions, refractive indices, grating pitch, etc.). In addition, the model includes a parameterization of the measurement tool itself (e.g., wavelengths, angles of incidence, polarization angles, etc.).

[0065] The above-described techniques for determining optimal focus and monitoring focus may be applied to any suitable process parameters. Process parameters generally refer to parameters used to control the processing conditions of the lithography system. Process parameters generally affect the pattern in a non-trivial way. By way of example, process parameters may correspond to focus offset, exposure dose, resist thickness, develop time and temperature, post exposure bake time and temperature and the like. The determined process settings may be used to improve the control of subsequent lithographic patterning and to determine whether the quality of the photolithographic pattern meets specified requirements. Process parameter determination or monitoring may be suitable for a wide variety of photolithography processes, as for example, photolithographic processes pertaining to semiconductor manufacturing, optical device manufacturing, micro-mechanical device manufacturing, magnetic recording data storage manufacturing and the like. Although process parameter determination or monitoring may be used in any of the

above processes, certain embodiments of the invention described herein is directed at semiconductor manufacturing for ease of discussion.

[0066] While certain implementations of this invention have been described in terms of several preferred embodiments, there are alterations, permutations, and equivalents, which fall within the scope of this invention. For example, although the term wafer was used throughout (e.g., semiconductor), it should be noted that the term wafer may also apply to workpieces, substrates, samples and the like (which are associated with other types of manufacturing) when certain techniques of the invention are used in other types of manufacturing. It should also be noted that there are many alternative ways of implementing the methods and apparatuses of the present invention. For example, although certain embodiments of the invention has been described in terms of photolithography that uses conventional radiation techniques, it should be noted that other lithography techniques may also be used, for example, UV lithography (which uses ultra violet), X-ray lithography (which uses X-ray), e-beam lithography (which uses electron beam), and ion beam (which uses ion beam).

[0067] Any suitable combination of hardware and/or software may be used to implement any of the above described techniques. In a general example, a metrology tool may comprise an illumination system which illuminates a target, a collection system which captures relevant information provided by the illumination system's interaction (or lack thereof) with a target, device or feature, and a processing system which analyzes the information collected using one or more algorithms. Metrology tools can generally be used to measure various radiation signals pertaining to structural and material characteristics (*e.g.,* material composition, dimensional characteristics of structures and films such as film thickness and/or critical dimensions of structures, overlay, etc.) associated with various semiconductor fabrication processes. These measurements can be used to facilitate process controls and/or yield efficiencies in the manufacture of semiconductor dies.

[0068] The metrology tool can comprise one or more hardware configurations which may be used in conjunction with certain embodiments of this invention. Examples of such hardware configurations include, but are not limited to, the following: Spectroscopic ellipsometer (SE), SE with multiple angles of illumination, SE measuring Mueller matrix elements (e.g. using rotating compensator(s)), single-wavelength ellipsometers, beam profile ellipsometer (angle-resolved ellipsometer), beam profile reflectometer (angle-resolved reflectometer), broadband reflective spectrometer (spectroscopic reflectometer), single-wavelength reflectometer, angle-resolved reflectometer, imaging system, and scatterometer (e.g. speckle analyzer)

[0069] The hardware configurations can be separated into discrete operational systems. On the other hand, one or more hardware configurations can be combined into a single tool. One example of such a combination of multiple hardware configurations into a single tool is further illustrated and described U.S. Pat. No. 7,933,026, which patent is herein incorporated by reference in its entirety for all purposes. Figure 7 shows, for example, a schematic of an exemplary metrology tool that comprises: a) a broadband SE (*e.g.,* 18); b) an SE (*e.g.,* 2) with rotating compensator (*e.g.*,., 98); c) a beam profile ellipsometer (*e.g.,* 10); d) a beam profile reflectometer (*e.g.,* 12); e) a broadband reflective spectrometer (*e.g.,* 14); and f) a deep ultra-violet reflective spectrometer (*e.g.,* 16). In addition, there are typically numerous optical elements (*e.g.,* 92, 72, 94, 70, 96, 74, 76, 80, 78, 98, 100, 102, 104, 32/33, 42, 84, 60, 62, 64, 66, 30, 82, 29, 28, 44, 50, 52, 54, 56, 46, 34, 36, 38, 40, and 86) in such systems, including certain lenses, collimators, mirrors, quarter-wave plates, polarizers, detectors, cameras, apertures, and/or light sources. The wavelengths for optical systems can vary from about 120 nm to 3 microns. For non-ellipsometer systems, signals collected can be polarization-resolved or unpolarized. Figure 7 provides an illustration of multiple metrology heads integrated on the same tool. However, in many cases, multiple metrology tools are used for measurements on a single or multiple metrology targets. Several embodiments of multiple tool metrology are further described, e.g., in U.S. 7,478,019 by Zangooie et al, entitled "Multiple tool and structure analysis", which patent is incorporated herein by reference in its entirety for all purposes.

[0070] The illumination system of certain hardware configurations may include one or more light sources. The one or more light sources may generate light having only one wavelength (*e.g.,* monochromatic light), light having a number of discrete wavelengths (*e.g.,* polychromatic light), light having multiple wavelengths (*e.g.,* broadband light), and/or light that sweeps through wavelengths, either continuously or hopping between wavelengths (*e.g.,* tunable sources or swept sources). Examples of suitable light sources are: a white light source, an ultraviolet (UV) laser, an arc lamp or an electrode-less lamp, a laser sustained plasma (LSP) source, for example, those commercially available from Energetiq Technology, Inc. of Woburn, Massachusetts, a supercontinuum source (such as a broadband laser source) such as those commercially available from NKT Photonics Inc. of Morganville, New Jersey, or shorter-wavelength sources such as x-ray sources, extreme UV sources, or some combination thereof. The light source(s) may also be configured to provide light having sufficient brightness, which in some cases may be a brightness greater than about 1 W/(nm cm2 Sr). The metrology system may also include a fast feedback to the light source for stabilizing its power and wavelength. Output of the light source can be delivered via free-space propagation, or in some cases delivered via optical fiber or light guide of any type.

[0071] In turn, one or more detectors or spectrometers are configured to receive via a collection optical elements illumination reflected or otherwise scattered from the surface of the specimen 4. Suitable sensors include charged coupled devices (CCD), CCD arrays, time delay integration (TDI) sensors, TDI sensor arrays, photomultiplier tubes (PMT), and other sensors. Measured spectra or detected signal data may be passed from each detector to the processor system 48 for analysis.

[0072] It should be recognized that the various steps described throughout the present disclosure may be carried out by a single processor system 48 or, alternatively, a multiple processor system 48. Moreover, different subsystems of the system of Figure 7, such as the spectroscopic ellipsometer, may include a computer system suitable for carrying out at least a portion of the steps described herein.

Therefore, the aforementioned description should not be interpreted as a limitation on the present invention but merely an illustration. Further, the one or more processor system 48 may be configured to perform any other step(s) of any of the method embodiments described herein.

[0073] In addition, the processor system 48 may be communicatively coupled to a detector system in any manner known in the art. For example, the one or more processor system 48 may be coupled to computing systems associated with the detector system. In another example, the detector system may be controlled directly by a single computer system coupled to processor system 48.

[0074] The processor system 48 of the metrology system may be configured to receive and/or acquire data or information from the subsystems of the system by a transmission medium that may include wireline and/or wireless portions. In this manner, the transmission medium may serve as a data link between the processor system 48 and other subsystems of the system of Figure 7.

[0075] Processor system 48 of the integrated metrology system may be configured to receive and/or acquire data or information (e.g., measurement results, extracted features, transformed datasets, curve fittings, determined best focus or other process settings, relationships between best and actual focus, focus corrections, etc.) from other systems by a transmission medium that may include wireline and/or wireless portions. In this manner, the transmission medium may serve as a data link between the processor system 48 and other systems (e.g., memory on-board metrology system, external memory, reference measurement source, or other external systems). For example, processor system 48 may be configured to receive measurement data from a storage medium (*e.g.*, internal or external memory) via a data link. For instance, spectral results obtained using the detection system may be stored in a permanent or semipermanent memory device (e.g., internal or external memory). In this regard, the spectral results may be imported from on-board memory or from an external memory system. Moreover, the processor system 48 may send data to other systems via a transmission medium. For instance, an optimum focus or focus correction determined by processor system 48 may be

communicated and stored in an external memory. In this regard, measurement results may be exported to another system.

[0076] Processor system 48 may include, but is not limited to, a personal computer system, mainframe computer system, workstation, image computer, parallel processor, or any other device known in the art. In general, the term "processor system" may be broadly defined to encompass any device having one or more processors, which execute instructions from a memory medium. Program instructions implementing methods such as those described herein may be transmitted over a transmission medium such as a wire, cable, or wireless transmission link. Program instructions may be stored in a computer readable medium (e.g., memory). Exemplary computer-readable media include read-only memory, a random access memory, a magnetic or optical disk, or a magnetic tape.

[0077] The metrology tool may be designed to make many different types of measurements related to semiconductor manufacturing. Certain embodiments of the invention for determining optimal focus may utilize such measurements. Additional metrology techniques for determining specific target characteristics may also be combined with the above-described focus determination techniques. For example, in certain embodiments the tool may measure spectra and determine characteristics of one or more targets, such as critical dimensions, overlay, sidewall angles, film thicknesses, process-related parameters (e.g., focus and/or dose). The targets can include certain regions of interest that are periodic in nature, such as for example gratings in a memory die. Targets can include multiple layers (or films) whose thicknesses can be measured by the metrology tool. Targets can include target designs placed (or already existing) on the semiconductor wafer for use, e.g., with alignment and/or overlay registration operations. Certain targets can be located at various places on the semiconductor wafer. For example, targets can be located within the scribe lines (e.g., between dies) and/or located in the die itself. In certain embodiments, multiple targets are measured (at the same time or at differing times) by the same or multiple metrology tools as described in US 7,478,019. The data from such measurements may be combined. Data from the metrology tool may

be used in the semiconductor manufacturing process, for example, to feed-forward, feed-backward and/or feed-sideways corrections to the process (e.g. lithography, etch) and therefore, might yield a complete process control solution.

[0078] As semiconductor device pattern dimensions continue to shrink, smaller metrology targets are often required. Furthermore, the measurement accuracy and matching to actual device characteristics increase the need for device-like targets as well as in-die and even on-device measurements. Various metrology implementations have been proposed to achieve that goal. For example, focused beam ellipsometry based on primarily reflective optics is one of them and described in the patent by Piwonka-Corle et al. (U.S. 5,608,526, "Focused beam spectroscopic ellipsometry method and system"). Apodizers can be used to mitigate the effects of optical diffraction causing the spread of the illumination spot beyond the size defined by geometric optics. The use of apodizers is described in the patent by Norton, U.S. 5,859,424, "Apodizing filter system useful for reducing spot size in optical measurements and other applications". The use of high-numerical-aperture tools with simultaneous multiple angle-of-incidence illumination is another way to achieve small-target capability. This technique is described, e.g. in the patent by Opsal et al, U.S. 6,429,943, "Critical dimension analysis with simultaneous multiple angle of incidence measurements".

[0079] Other measurement examples may include measuring the composition of one or more layers of the semiconductor stack, measuring certain defects on (or within) the wafer, and measuring the amount of photolithographic radiation exposed to the wafer. In some cases, metrology tool and algorithm may be configured for measuring non-periodic targets, see e.g. "The Finite Element Method for Full Wave Electromagnetic Simulations in CD Metrology Using Scatterometry" by P. Jiang et al (pending U.S. 61/830536, K-T disclosure P4063) or "Method of electromagnetic modeling of finite structures and finite illumination for metrology and inspection" by A. Kuznetsov et al. (pending U.S. 61/761146 or KT disclosure P4082).

[0080] Measurement of parameters of interest usually involves a number of algorithms. For example, optical interaction of the incident beam with the sample is

modeled using EM (electro-magnetic) solver and uses such algorithms as RCWA, FEM, method of moments, surface integral method, volume integral method, FDTD, and others. The target of interest is usually modeled (parametrized) using a geometric engine, or in some cases, process modeling engine or a combination of both. The use of process modeling is described in "Method for integrated use of model-based metrology and a process model," by A. Kuznetsov et al. (pending U.S. 61/738760, P4025). A geometric engine may be implemented, for example, in AcuShape software product of KLA-Tencor of Milpitas, CA.

[0081] Collected data can be analyzed by a number of data fitting and optimization techniques an technologies including libraries, Fast-reduced-order models; regression; machine-learning algorithms such as neural networks, support-vector machines (SVM); dimensionality-reduction algorithms such as, e.g., PCA (principal component analysis), ICA (independent component analysis), LLE (local-linear embedding); sparse representation such as Fourier or wavelet transform; Kalman filter; algorithms to promote matching from same or different tool types, and others.

[0082] Collected data can also be analyzed by algorithms that do not include modeling, optimization and/or fitting e.g. provisional patent application 61/745981, which is incorporated herein by reference.

[0083] Computational algorithms are usually optimized for metrology applications with one or more approaches being used such as design and implementation of computational hardware, parallelization, distribution of computation, load-balancing, multi-service support, dynamic load optimization, etc. Different implementations of algorithms can be done in firmware, software, FPGA, programmable optics components, etc.

[0084] The data analysis and fitting steps may be used to pursue one of the following goals: measurement of CD, SWA, shape, stress, composition, films, bandgap, electrical properties, focus/dose, overlay, generating process parameters (e.g., resist state, partial pressure, temperature, focusing model), and/or any combination thereof; modeling and/or design of metrology systems; and modeling, design, and/or optimization of metrology targets.

[0085] Certain embodiments of the present invention presented here generally address the field of semiconductor metrology and process control, and are not limited to the hardware, algorithm/software implementations and architectures, and use cases summarized above.

[0086] Although the foregoing invention has been described in some detail for purposes of clarity of understanding, it will be apparent that certain changes and modifications may be practiced within the scope of the appended claims. It should be noted that there are many alternative ways of implementing the processes, systems, and apparatus of the present invention. Accordingly, the present embodiments are to be considered as illustrative and not restrictive, and the invention is not to be limited to the details given herein.

CLAIMS

What is claimed is:

1. A method of determining optimal focus for a photolithography system, the method comprising:

acquiring a plurality of optical signals from a particular target located in a plurality of fields on a semiconductor wafer, wherein the fields were formed using different process parameters, including different focus values;

extracting a feature from the optical signals related to changes in focus;

fitting a symmetric curve to the extracted feature of the optical signals as a function of focus; and

determining and reporting an extreme point in the symmetric curve as an optimal focus for use in the photolithography system.

2. The method of claim 1, wherein the extracted feature is a combination of one or more of the optical signals that is most sensitive to changes in focus, as compared to other combinations of one or more of the optical signals.

3. The method of claim 1, wherein the extracted feature is a linear combination of the optical signals.

4. The method of claim 1, wherein the extracted feature is a non-linear combination of the optical signals.

5. The method of claim 1, wherein the extracted feature is a plurality of second optical signals that are created from a transformation of the first optical signals.

6. The method of claim 5, wherein the transformation is accomplished using a principal component analysis (PCA), Independent Component Analysis (ICA), or Local Linear Embedding (LLE) algorithm.

7. The method of claim 6, wherein the transformation is accomplished using a principal component analysis (PCA) and the extracted feature is the second optical signals with respect to a first principal component resulting from the PCA transformation.

8. The method of claim 1, wherein the optical signals are acquired from a focus-exposure matrix (FEM) wafer.

9. The method of claim 1, wherein the symmetric curve fitted to the extracted feature is a parabola.

10. The method of claim 1, further comprising:

repeating the operations for acquiring, extracting, fitting, and determining and reporting for a plurality of wafers to determine a plurality of optimal focus; and

determining a relationship between an actual focus of the photolithography system and an optimal focus.

11. The method of claim 1, wherein the optical signals are acquired using one or more of the following: spectroscopic ellipsometry, Mueller matrix spectroscopic ellipsometry, spectroscopic reflectometry, spectroscopic scatterometry, beam profile reflectometry, beam profile ellipsometry, a single wavelength, a single discrete wavelength range, or multiple discrete wavelength ranges.

12. A system for inspecting or measuring a specimen, comprising:

an illuminator for generating illumination;

illumination optics for directing the illumination towards a particular target located in a plurality of fields on a semiconductor wafer, wherein the fields were formed using different process parameters, including different focus values;

collection optics for directing a plurality of optical signals from the particular target located in the plurality of fields in response to the illumination to a detector system;

the detector system for acquiring the plurality of optical signals from the particular target from the plurality of fields in response to the illumination; and

a processor and memory configured for performing the following operations:

extracting a feature from the optical signals related to changes in focus;

fitting a symmetric curve to the extracted feature of the optical signals as a function of focus; and

determining and reporting an extreme point in the symmetric curve as an optimal focus for use in the photolithography system.

13. The system of claim 12, wherein the extracted feature is a combination of one or more of the optical signals that is most sensitive to changes in focus, as compared to other combinations of one or more of the optical signals.

14. The system of claim 12, wherein the extracted feature is a linear combination of the optical signals.

15. The system of claim 12, wherein the extracted feature is a non-linear combination of the optical signals.

16. The system of claim 12, wherein the extracted feature is a plurality of second optical signals that are created from a transformation of the first optical signals.

17. The system of claim 16, wherein the transformation is accomplished using a principal component analysis (PCA), Independent Component Analysis (ICA), or Local Linear Embedding (LLE) algorithm.

18. The system of claim 17, wherein the transformation is accomplished using a principal component analysis (PCA) and the extracted feature is the second optical signals with respect to a first principal component resulting from the PCA transformation.

19. The system of claim 12, wherein the optical signals are acquired from a focus-exposure matrix (FEM) wafer.

20. The system of claim 12, wherein the symmetric curve fitted to the extracted feature is a parabola.

21. The system of claim 12, wherein the processor and memory are further configured for:

repeating the operations for acquiring, extracting, fitting, and determining and reporting for a plurality of wafers to determine a plurality of optimal focus; and

determining a relationship between an actual focus of the photolithography system and an optimal focus.

22. The system of claim 12, wherein the optical signals are acquired using one or more of the following: spectroscopic ellipsometry, Mueller matrix spectroscopic ellipsometry, spectroscopic reflectometry, spectroscopic scatterometry, beam profile reflectometry, beam profile ellipsometry, a single wavelength, a single discrete wavelength range, or multiple discrete wavelength ranges.

23. The system of claim 12 in the form of an ellipsometer, the sytsem further comprising:

a polarization state generator for producing a polarized state in the illumination; and

a polarization state analyzer for analyzing a polarized state of the optical signals.