Registration models are well developed for environments using similar types of lithography equipment. In this arrangement, a 1:1 field size matching is the standard registration requirement. However, there is now significant interest in mix-and-match lithography utilizing systems with extremely large field sizes to increase wafer throughput on less critical process levels. This approach is widely accepted as a valuable technique to enhance cost of ownership for a manufacturing environment. For example, 1x fields are presently twice the field size of advanced reduction steppers. Therefore, application of traditional 1:1 registration analysis techniques to such mix-and-match scenarios does not yield optimal results. In order to properly characterize and optimize such a 2:1 matching scheme, one must consider the types of registration errors present and their sources.

In this study, a large field 1x stepper was matched to an advanced 5x reduction stepper using a 2:1 field matching scheme. The 1x field is a 44 x 22 mm rectangle that is symmetrically aligned to two 22 x 22 mm 5x reduction fields. Overlay measurements were collected at 33 sites per reduction field (or 66 sites per Ultratech field) and the resulting data was analyzed using a modified grid registration model that fully supports the 2:1 field matching geometry.

Two complementary optimization techniques were developed, the first of which assumes corrective action only on the 1x stepper. The more sophisticated approach supports corrective action on both the 1x and 5x reduction stepper. Next, both techniques were applied to the measured mix-and-match data with the results suggesting a specific set of corrective action that could be applied to the 1x and the 5x reduction steppers. Based on these results, it was found that there is a substantial registration benefit to exerting simultaneous corrections on both stepper types as opposed to controlling each stepper individually.
1.0 Introduction

Until recently, the global competition in integrated circuit fabrication has been based on both technological and economic factors. However, fabrication costs are becoming the single dominant issue as the price of new high volume production facilities approaches the billion dollar level [1]. A new measure of fabrication affordability called “technology drag” has been proposed by Hutcheson et. al. [2]. Their analysis is based on non-linear chaos theory. It suggests that new cash flow is slowing and that as soon as the late 1990s it will cost more to invest in new fabrication facilities and equipment than the potential sales would return to the company. This raises the issue of what can be done to reduce technology drag and help restore corporate profitability. Since lithography equipment represents a large investment cost, it is also an excellent area to pursue cost savings [1]. One technique that has been extremely successful in containing lithographic costs is mix-and-match, or intermix, lithography.

Historically, mix-and-match lithography has been used to bridge different systems to derive the maximum benefits of each. In the early 1980s, mix-and-match was first used between scanners and steppers to take advantage of the installed base of scanners while achieving the resolution and overlay of the steppers for critical levels [3]. More recently, mix-and-match lithography has been used between steppers and extremely expensive, high performance lithography equipment such as direct write on wafer e-beam or x-ray systems [4]. This approach offered significant cost savings while maintaining technological advantages.

In general, a less costly and higher throughput lithography tool is used for the non-critical levels, while the higher resolution and more expensive lithography tool is only used on critical levels. This approach has been shown to provide dramatic cost of ownership advantages over using the more expensive critical level lithography tool on all of the levels [1,5]. Higher throughput for non-critical levels can be achieved by having systems with an extremely high speed stage or a large lens field size to reduce the number of exposure steps required to completely expose each wafer. However, this larger field size must be an integer multiple of the field size of the second lithography tool in order to take advantage of the potential reduction in exposure steps. For example, the Ultratech 2244i 1x stepper has a rectangular field size of 22 x 44 mm, which is twice the 22 x 22 mm square field size of advanced 5x reduction steppers [6].

In order to obtain maximum lithographic performance when using multiple lithographic systems, each system must be calibrated or matched to the other systems [7,8]. Extensive analysis and modeling of overlay errors have been developed for the matching of the same model or similar type systems. These overlay errors can be divided into two categories: intrafield and interfield systematic sources. The intrafield sources (dX and dY) model the overlay error sources within one field [9,10,11]:

\[
\begin{align*}
\text{d}X(x,y) &= T_{ix} + M_{x}x - \Theta_{y}y + \Psi_{x}x^2 + \Psi_{xy}xy + D_{3x}(x^2+y^2) + D_{5x}(x^2+y^2)^2 \\
\text{d}Y(x,y) &= T_{iy} + M_{y}y + \Theta_{x}x + \Psi_{y}y^2 + \Psi_{xy}xy + D_{3y}(x^2+y^2) + D_{5y}(x^2+y^2)^2
\end{align*}
\]
where \( x \) and \( y \) are the coordinate location relative to the center of the field. For these equations, the linear terms include die shift in \( x \) (\( T_{ix} \)) and \( y \) (\( T_{iy} \)), magnification in \( x \) (\( M_x \)) and \( y \) (\( M_y \)) and rotation (\( \Theta_i \)). The nonlinear terms include trapezoid in \( x \) (\( \Psi_x \)) and \( y \) (\( \Psi_y \)), third order (\( D_3 \)) and fifth order (\( D_5 \)). The interfield sources (\( E_x \) and \( E_y \)) model the grid stage motion errors across the wafer [10,11]:

\[
E_x(X,Y) = T_{gx} + S_xX - \Theta_gY - \Phi Y \tag{3}
\]
\[
E_y(X,Y) = T_{gy} + S_yY + \Theta_gX \tag{4}
\]

where \( X \) and \( Y \) are the coordinate locations on the wafer. The interfield sources include translation error in \( X \) (\( T_{gx} \)) and \( Y \) (\( T_{gy} \)), the wafer scaling magnification in \( X \) (\( S_x \)) and \( Y \) (\( S_y \)), wafer rotation (\( \Theta_g \)), and wafer orthogonality (\( \Phi \)).

For these intrafield and interfield models, the field sizes between the two lithography systems are identical, which implies 1:1 interfield matching. However, it has already been established that mix-and-match lithography frequently requires \( n:1 \) field matching. The application of 1:1 registration analysis techniques to such mix-and-match scenarios does not yield optimal overlay results. In order to properly characterize and optimize such \( n:1 \) matching schemes, one must consider the types of registration errors present and their sources. This paper will develop an overlay model for the 2:1 matching case and compare it to experimental 2:1 field overlay data.

Optimization of overlay for mix-and-match lithography can use several different techniques since multiple systems are involved. For this study, two complementary optimization techniques were developed, the first of which assumes corrective action only on the second system aligning to the first system. A more sophisticated approach supports corrective action on both steppers. These two techniques were applied to the measured mix-and-match data with the results suggesting a specific set of corrective actions which could be applied to both steppers.

## 2.0 Overlay Modeling

### 2.1 Grid Modeling

It is possible to have \( n:1 \) field matching when the field area on at least one stepper is \( n \) times as large as the field area on the other steppers in the production line. An example of 2:1 field matching occurs with the mixing of the Ultratech 2244i 1x system (field size 22 by 44 mm) with 5x reduction steppers from Nikon, Canon and ASM (field size 22 by 22 mm). The specific overlay model developed in this paper will be for 2:1 matching, but it can easily be extended to the general \( n:1 \) matching case. This analysis will refer to the 2244i and generic large field systems as a wide field stepper, or \( w \) in variable subscripts. The 5x reduction steppers and systems similar to...
them will be referred to as narrow field steppers, or \( n \) in variable subscripts. It is important to note that the following analysis is independent of the magnification reduction ratio of either the wide field or the narrow field systems.

The mix-and-match case to be modeled assumes the base layer (level 1) is blind stepped onto the wafer using a narrow field stepper. Level 2 is then patterned by a wide field stepper using alignment targets placed on level 1. For each stepped position, the wide field stepper simultaneously patterns two horizontally spaced narrow stepper fields as shown in Figure 1. Here \( \Delta X \) and \( \Delta Y \) represent the stage motion in the \( X \) and \( Y \) directions respectively. In order to simplify the following numerical analysis, the pattern of measured overlay structures should be symmetric across \( X \) and \( Y \) axes in both the narrow field and wide field coordinate systems.

The grid stage motion errors on the narrow field stepper can be described using equations (3) and (4):

\[
V_{nx}(X_n,Y_n) = T_{gxn} + S_{xn}X_n - \Theta_{gn}Y_n - \Phi Y_n \\
V_{ny}(X_n,Y_n) = T_{gyn} + S_{yn}Y_n + \Theta_{gn}X_n
\]

Where \( X_n \) and \( Y_n \) are the \( X-Y \) coordinates of the center of the specified narrow field relative to the center of the wafer. Note that all points residing in the same narrow field will have the same narrow field grid coordinates regardless of their position within the field. Similarly, the grid stage motion errors induced on the wide field stepper can be described using equations (3) and (4):

\[
V_{wx}(X_w,Y_w) = T_{gxw} + S_{xw}X_w - \Theta_{gw}Y_w - \Phi Y_n \\
V_{wy}(X_w,Y_w) = T_{gyw} + S_{yw}Y_w + \Theta_{gw}X_w
\]

Where \( X_w \) and \( Y_w \) are the \( X-Y \) coordinates of the center of the specified wide field relative to the center of the wafer. Again, all points residing in the same wide field will have the same wide field grid coordinates regardless of their position within the field.

The total error vectors for both steppers can be mathematically added as follows:

\[
V_{x\text{total}}(X_n,Y_n,X_w,Y_w) = T_{gxn} + S_{xn}X_n + \Theta_{gn}Y_n - \Phi Y_n + T_{gxw} + S_{xw}X_w + \Theta_{gw}Y_w - \Phi Y_w \\
V_{y\text{total}}(X_n,Y_n,X_w,Y_w) = T_{gyn} + S_{yn}Y_n + \Theta_{gn}X_n + T_{gyw} + S_{yw}Y_w + \Theta_{gw}X_w
\]

where the variables and coefficients in equations (5) through (10) are defined in Table 1.

It is important to note that the grid error terms described above are not necessarily actual, but rather are apparent or effective errors. The variables can be broken up into separable and
inseparable coefficients. Inseparable coefficients describe errors that are fully correctable by application at either stepper as defined in Table 2. Combinations of stepper effects for this type of component are additive. Separable components require independent corrective action on both steppers to achieve zero overlay error. This occurs since intrafield errors are coupled to the grid errors. For example, it can be shown that wide field magnification error can manifest itself as an apparent combination wide and narrow field scale error. Another interesting effect is that wide field die rotation can induce an apparent or effective grid rotation. However, the mathematical tractability of accounting for the full grid and intrafield effects is much more complex. Future research will concentrate on the incorporation of grid and intrafield effects simultaneously.

2.2 Model Algorithm

Figure 2 shows a pictorial flow chart of the 2:1 model algorithm. The first step is the collection of the overlay data $M_x(X,Y,x,y)$ and $M_y(X,Y,x,y)$ using the experimental methods that will be discussed in section 3.0. Here $X$ and $Y$ are the coordinate location on the wafer while $x$ and $y$ are the coordinate location relative to the center of the field.

Steps 2, 3, 4 and 5 involve a series of transformations of the total error vectors described in equations (9) and (10). First, the narrow field errors are translated to the wide field coordinate system using the geometric relationship between the narrow and wide fields. Next, the inseparable composite coefficients identified in Table 2 are substituted into the equations to yield:

\[
V^*_x (X_n,Y_n,X_w,Y_w) = T^*_x + S_{xn} X_n + \Theta_{gn} Y_n - \Phi^*_n + S_{xw} X_w + \Theta_{gw} Y_w
\]

(11)

\[
V^*_y (X_n,Y_n,X_w,Y_w) = T^*_y + S_{yn} Y_n - \Theta_{gn} X_n - \Theta_{gw} X_w
\]

(12)

This technique is tantamount to solving for grid corrections in the wide field stepper coordinate system. In this situation, the model equations are actually overdetermined because of the inseparable terms in the grid equations.

The objective of step 6 is to solve for the coefficients of equations (11) and (12). This involves creating a system of equations that can be solved by standard least squares techniques using the overlay data $M_x(X,Y)$ and $M_y(X,Y)$. The equations can be represented in the standard matrix form:

\[
M \tilde{x} = \tilde{b}
\]

(13)

where matrix $M$ and the vectors $\tilde{x}$ and $\tilde{b}$ are defined in appendix A.

Finally, the model results obtained from step 6 are subtracted from the overlay data to create the residual arrays $R^*_x(X,Y)$ and $R^*_y(X,Y)$. This is the difference between the measured data points and the estimate of the overlay error at that point:

\[
R^*_x(X,Y) = M_x(X,Y) - V^*_x (X,Y)
\]

(14)

\[
R^*_y(X,Y) = M_y(X,Y) - V^*_y (X,Y)
\]

(15)
If additional assumptions are made about the pattern of overlay measurements, it is possible to combine intrafield terms into the mathematical algorithm. This scenario will be analyzed fully in a future paper.

3.0 Experimental Methods

3.1 Lithography Equipment

A sample 2:1 field matching was performed using an Ultratech Stepper model 2244i as the wide field stepper and a Canon model FPA 2500i2 for the narrow field stepper. The Ultratech Stepper model 2244i, which will be referred to as the 2244i or the widefield stepper, is based on the 1x Wynne-Dyson Hershel lens design applied to i-line lithography with a field size of 22 x 44 field size [6]. The 2244i lens employs 0.32 numerical aperture i-line optics with a broadband of illumination of 20 nanometers (355 to 375 nanometers). Also incorporating i-line optics, the Canon FPA 2500i2 stepper provides a field size of 22 x 22 mm square. Hence this allows two fields from the narrow field stepper to be positioned within a single 22 x 44 mm field on the Ultratech 2244i.

3.2 Reticle Field Layout

In order to provide the necessary grid and intrafield overlay measurements for 2:1 field optimization, a characterization reticle set for both steppers was designed. Proper design of this reticle set required attention to image orientations and magnification of each lithography tool. The field layout for this set consisted of overlay and blindstep metrology patterns located within the field as shown in Figure 3. A standard box-in-frame measurement structure is positioned at each overlay location for subsequent automated measurement, where the narrow field stepper defines the outer frame structure and the wide stepper defines the corresponding inner box structure. This design provides a total of 49 overlay locations per narrow field arranged in a periodic array of 7 rows by 7 columns extending to the 22 x 22 mm field boundary. However, only 33 fields covering the narrow field were selected for measurement.

3.3 Process Description

The backend segment of a submicron CMOS process was evaluated in the 2:1 field matching of this project. First, the narrow field stepper patterned the reference grid on a metallized substrate film. No intentional grid or intrafield errors were applied by the narrow field stepper for this reference level. Subsequent etching of the metal film transferred the reference level, which include alignment targets for the Ultratech 2244i. Next, both TEOS and nitride films were deposited over the patterned metal to simulate the process film stacks encountered at a dielectric mask level. Alignment of dielectric mask to the metal level was then performed using the Ultratech 2244i. A cross sectional view of the entire composite film stack is shown in Figure 4.
Nine wafers of eight inch diameter were evaluated. Each contained a total of 48 narrow field or 24 2244i fields as shown in Figures 5a and 5b respectively. A one-micron film of UCB-JSR ix500EL photoresist was coated and prebaked for 60 seconds at 90 °C prior to exposure. Enhanced Global Alignment (EGA) using nine Ultratech 2244i fields was utilized. Figure 5 shows the nine EGA sites, which are marked with an E. After exposing, the wafers were post exposure baked for 60 seconds at 120 °C and then developed for 60 seconds in PPD-523 (NMD-3 Metal Ion Free) developer for later overlay measurement.

3.4 Ultratech 2244i Alignment

After sampling all nine EGA sites, the stepper calculated grid corrections based on the grid model equations (3) and (4), which are applicable for the wide field stepper coordinate system. Standard linear regression techniques were then applied in the solution of equations (3) and (4). Grid corrections derived from the linear regression were then utilized to position all 24 final exposure field locations on the 2244i level. During the EGA and exposure, the 2244i was configured for local focus and image leveling to compensate for wafer flatness irregularities.

Alignment targets for the Ultratech Stepper were located along a horizontal scribe across the top of each narrow field. These target designs are a standard target with a width of 2 microns and are of a darkfield (valley) polarity. Two alignment targets per wide field, with one from both the left and right adjacent narrow fields, are used.

Implicit in the widefield grid corrections are the contributions from both the left and right narrow fields. This occurred because the 2244i was simultaneously sampling two alignment targets per widefield, one from the left narrow field and one from the right narrow field. Although the 2244i supports the capability to apply additional systematic grid corrections to the regressed grid corrections, additional corrections were not implemented. Consequently, the resulting 2:1 field overlay matching is only corrected with the traditional grid corrections from the widefield stepper.

3.5 Metrology

Overlay was measured on a KLA 5700 Coherence Probe Microscope using 66 box-in-frame structures spread across the Ultratech field as shown in Figure 3. A total of 14 Ultratech fields or 28 Canon fields were measured on each wafer at the locations designated by a \( \star \) in Figure 5a. With 24 narrow fields per wafer and 33 locations per field, 924 overlay measurements were collected per wafer. All the overlay measurements were indexed with the appropriate coordinate locations to distinguish grid location and intrafield location. It is essential for proper analysis to allow each overlay measurement to be associated with its appropriate 2:1 field location.

This field sampling strategy, which covers the full extent of the wafer, provides sufficient statistical degrees of freedom for extraction of grid parameters in the 2:1 mix-and-match application. Also, when examining the pooled uncorrected mix-and-match error prior to modeling
all corrections, a sample size of 924 provides a reasonable confidence interval for typical metrics such as the standard deviation and mean.

Blindstep or grid performance of the first level with the narrow field stepper was measured using the KLA 5700. Both grid placement accuracy and precision are crucial for 2:1 field matching. These measurements were done to validate the integrity of the grid for the 2:1 field matching. The technique to quantify blindstep performance was based on using a slight overlap of the edges of adjacent narrow fields with standard box-in-frame structures. Figure 6 illustrates the four locations available for measurement of the narrow field grid, six locations along the vertical axis of the field for left to right stage stepping, and five locations along the top horizontal axis for top to bottom stage stepping. For these terms, the vertical axis is the most crucial for 2:1 field matching. Using the KLA 5700 to measure the box-in-frame structure allowed determination of both stage repeatability and systematic blind step offsets. However, since only relative positions of adjacent narrow fields can be measured with this technique, absolute grid accuracy cannot be extracted.

The KLA 5700 uses Coherence Probe technology to measure overlay [12]. Characterization was performed on the system to assure that the error due to the tool was negligible. Multiple measurements were taken on the overlay targets during the tool setup to determine the tool variance. Ten measurements on the overlay targets displayed a 3 sigma of 7 nanometers. The Tool Induced Shift (TIS) has been characterized and seen to be less than 10 nanometers for layers up to 15 microns thick.

4.0 Results and Analysis

4.1 Total Overlay

It is useful to examine the x and y distribution of overlay errors to provide insight into any systematic trends or unique characteristics of the data set. Histograms of the 2:1 field matching total overlay are depicted in Figures 7a and 7b. The data set consists of 66 measurements per field, 10 fields per wafer, over three wafers for a total of 1980 measurements. The summary statistics are listed in Table 3. The visual appearance of both histograms suggests a non-normal behavior. This was verified by a Shapiro-Wilk normality test of the x and y distributions as shown in Table 3. Thus, 3 sigma terminology is misleading as an indicator of 99.7% overlay performance. A better indicator is the 99.5% range based on quantities, which are 0.292 and 0.267 microns for x and y. These 99.5% range values are significantly smaller than the three sigma values.

4.2 Comparison of Grid Models

A total of three different grid models were studied using one wafer from this data set. These models included the 2:1 model algorithm developed in section 2.0, the narrow field stepper as the
reference level, and the wide field stepper as the reference level. Table 4 provides a summary of the grid model coefficients for these scenarios. The 2:1 model grid coefficients were calculated using a beta site version of Mono-Lith® containing the new algorithm, while model coefficients for the other two models were determined from KLASS III® software[13]. The one sigma error for \( X \) and \( Y \) is included along with the one sigma residual error after implementation of the modeled grid corrections. The residual errors allow a useful comparison of the relative fit of each grid model.

First, notice that the mean translation errors for \( X \) and \( Y \) of each model are comparable. This implies that translation errors are not strongly coupled to any other components for this particular data set. Next, consider the 2:1 model coefficients and raw and residual errors. The inseparable \( Y \) scale \( (S_y^*) \) value is relatively small at -0.27 ppm. This demonstrates close \( Y \) scale grid matching of the widefield 2244i to the narrow field. This is to be expected since the \( Y \) scale component is not affected by the 2:1 field matching geometry. Orthogonality \( (\Phi^*) \) of 1.27 ppm indicates a relatively large correction. It is possible that coupling of intrafield errors is resulting in an apparent grid rotation. This is due to the fact that both the wide field and narrow field can induce a grid rotation. The \( X \) scale coefficients for the narrow and widefield steppers are comparable with opposite signs. A similar effect also occurs for the narrow and wide field rotation coefficients, which are 3.85 and -3.69 ppm respectively. With the grid values for \( X \) scale and rotation of similar and of opposite polarity, it appears that the first level narrow field grid errors are well compensated during mix-and-match alignment.

The last four rows of Table 4 include the one sigma \( x \) and \( y \) errors of the raw data and the residual error after implementation of the different grid models. For the 2:1 model there is a 29% improvement in the \( x \) error, while the \( y \) improvement is only 5%. The narrow field and wide field models do not show as large reductions in the residuals. The \( x \) improvement for the narrow and wide field models are 16% and 18% respectively. The \( x \) and \( y \) improvements for both are approximately 2%, which is comparable to the 2:1 model. Figures 8 through 10 show histograms depicting the \( x \) and \( y \) distributions of the residual errors for the 2:1 model, the narrowfield model and the widefield model. The histograms offer further support that the 2:1 algorithm provides an improvement over the other two models in the \( x \) overlay error distribution. In contrast, the \( y \) overlay error distribution is comparable for all three models.

A summary of the 2:1 model coefficients for three wafers is listed in Table 5. The same coefficient characteristics are apparent for all three wafers. Residual error effects are also similar, showing up to a 40 nanometer improvement in \( x \) sigma and an essentially insignificant improvement in \( y \).

### 4.3 Intrafield Effects

Although the benefits of the 2:1 grid algorithm on the overlay error are evident, the residual errors are still quite large. This is due to strong intrafield effects of the narrow and widefield steppers. Also, an optimum 2:1 field matching requires simultaneous correcting for grid and intrafield effects. Future work will concentrate on addressing this challenge. However, a preliminary
analysis utilizing a narrow field magnification in addition to the 2:1 grid algorithm is illustrated in the $x$ and $y$ histograms of Figures 11. The resulting residual error for this approach is 86 and 105 nanometers for $x$ and $y$ respectively, or a 35% and 21% improvement.

5.0 Conclusions

With the continued escalating costs of advanced lithography equipment for the semiconductor industry, the advantages of mix-and-match lithography as a cost control measure are gaining worldwide recognition. However, the optimization of registration for 2:1 field matching provides new challenges not present in the classical 1:1 case.

The fundamental issues for 2:1 grid models have been described in detail. A unique 2:1 grid algorithm that utilizes corrective action on both narrow and wide field steppers has been developed. It was compared to two classical grid approaches, one based on the narrow field stepper and the other based on the widefield stepper. Experimental results comparing the three models illustrate the superior performance of the 2:1 algorithm. This model shows a 29% improvement in the $x$ overlay error over the other two models.

The unique characteristics of 2:1 field matching are apparent in the coupling of intrafield and grid parameters. First, there is coupling of intrafield die rotation with grid rotation. Second, the relative $X$ scale of the narrow and widefield steppers allows compensation of $x$ magnification.

It is possible to include intrafield terms with the 2:1 field model algorithm developed in this study to create a comprehensive model for 2:1 matching. This is being pursued as part of future work in the optimization of 2:1 mix-and-match lithography.
6.0 References


### 7.0 Appendix A

The following system of equations is used in the solution of the 2:1 algorithm. The equations are represented in the standard matrix form of $M \bar{x} = \bar{b}$.

$$
M = \begin{bmatrix}
0 & -\Sigma Y_w & \Sigma X_w & 0 & -\Sigma Y_w & 0 & +\Sigma X_n & 0 \\
0 & N & +\Sigma X_w & 0 & +\Sigma Y_w & 0 & +\Sigma X_n & 0 \\
+\Sigma Y_w & -\Sigma X_w & -\Sigma Q_1 & +\Sigma Q_2 & -\Sigma Q_2 & +\Sigma Y_w^2 & -\Sigma Q_3 & +\Sigma Q_4 \\
+\Sigma X_w & 0 & -\Sigma Q_2 & +\Sigma X_w^2 & 0 & -\Sigma Q_2 & -\Sigma Q_2 & +\Sigma Q_3 \\
0 & +\Sigma Y_w & +\Sigma Q_2 & 0 & +\Sigma Y_w^2 & 0 & +\Sigma Q_4 & 0 \\
-\Sigma Y_w & 0 & +\Sigma Y_w^2 & -\Sigma Q_2 & 0 & +\Sigma Y_w^2 & +\Sigma Y_w^2 & -\Sigma Q_4 \\
+\Sigma Y_w & -\Sigma X_n & -\Sigma Q_3 & +\Sigma Q_2 & -\Sigma Q_2 & -\Sigma Y_w^2 & -\Sigma Q_6 & +\Sigma Q_4 \\
+\Sigma X_n & 0 & -\Sigma Q_4 & +\Sigma Q_3 & 0 & -\Sigma Q_4 & -\Sigma Q_4 & +\Sigma X_n^2 \\
\end{bmatrix}
$$

<table>
<thead>
<tr>
<th>$T_x^*$</th>
<th>$T_y^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Theta_w$</td>
<td>$S_{xw}$</td>
</tr>
<tr>
<td>$S_{yw}$</td>
<td>$S_{yn}$</td>
</tr>
<tr>
<td>$\Phi^*$</td>
<td>$S_{xn}$</td>
</tr>
</tbody>
</table>

$$
\bar{x} = \begin{bmatrix}
T_x^* \\
T_y^* \\
\Theta_w \\
S_{xw} \\
S_{yw} \\
S_{yn} \\
\Phi^* \\
S_{xn} \\
\end{bmatrix}, \quad \bar{b} = \begin{bmatrix}
\Sigma M_x(i) \\
\Sigma M_y(i) \\
-\Sigma M_x(i)Y_w(i) - M_y(i)X_w(i) \\
\Sigma M_y(i)Y_w(i) \\
-\Sigma M_y(i)Y_w(i) \\
\Sigma M_x(i)Y_w(i) - M_y(i)X_n(i) \\
\Sigma M_x(i)X_n(i) \\
\end{bmatrix}
$$

where:

$$
Q_1 = (X_w^2 + Y_w^2) \quad Q_2 = (X_w Y_w) \quad Q_3 = (X_nX_w + Y_w^2) \\
Q_4 = (X_nY_w) \quad Q_5 = (X_nX_w) \quad Q_6 = (X_n^2 + Y_w^2)
$$
<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{nx}$</td>
<td>Total X error vector contribution of the narrow field stepper.</td>
</tr>
<tr>
<td>$V_{ny}$</td>
<td>Total Y error vector contribution of the narrow field stepper.</td>
</tr>
<tr>
<td>$V_{wx}$</td>
<td>Total X error vector contribution of the wide field stepper.</td>
</tr>
<tr>
<td>$V_{wy}$</td>
<td>Total Y error vector contribution of the wide field stepper.</td>
</tr>
<tr>
<td>$V_{x_{total}}$</td>
<td>Combined total X error vector of the wide and narrow field steppers.</td>
</tr>
<tr>
<td>$V_{y_{total}}$</td>
<td>Combined total Y error vector of the wide and narrow field steppers.</td>
</tr>
<tr>
<td>$T_{gxn}$</td>
<td>X translation error induced by the narrow field stepper. (µm)</td>
</tr>
<tr>
<td>$T_{gyn}$</td>
<td>Y translation error induced by the narrow field stepper. (µm)</td>
</tr>
<tr>
<td>$T_{gxw}$</td>
<td>X translation error induced by the wide field stepper. (µm)</td>
</tr>
<tr>
<td>$T_{gyw}$</td>
<td>Y translation error induced by the wide field stepper. (µm)</td>
</tr>
<tr>
<td>$S_{xn}$</td>
<td>X scale error induced by the narrow field stepper. (ppm)</td>
</tr>
<tr>
<td>$S_{yn}$</td>
<td>Y scale error of the narrow field stepper. (ppm)</td>
</tr>
<tr>
<td>$S_{xw}$</td>
<td>X scale error of the wide field stepper. (ppm)</td>
</tr>
<tr>
<td>$S_{yw}$</td>
<td>Y scale error of the wide field stepper. (ppm)</td>
</tr>
<tr>
<td>$\Theta_{gn}$</td>
<td>Wafer rotation error of the narrow field stepper. (µ radians)</td>
</tr>
<tr>
<td>$\Theta_{gw}$</td>
<td>Wafer rotation error of the wide field stepper. (µ radians)</td>
</tr>
<tr>
<td>$\Phi_{n}$</td>
<td>Wafer orthogonality error of the narrow field stepper. (ppm)</td>
</tr>
<tr>
<td>$\Phi_{w}$</td>
<td>Wafer orthogonality error of the wide field stepper. (ppm)</td>
</tr>
</tbody>
</table>

*Table 1: Definitions of the variables in the grid stage motion equations.*
Table 2: Definitions of inseparable composite coefficients.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Definition</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{gx}$</td>
<td>$T_{gxu} + T_{gxw}$</td>
<td>The X translation error induced by the combination of both steppers. (µm)</td>
</tr>
<tr>
<td>$T_{gy}$</td>
<td>$T_{gyu} + T_{gyw}$</td>
<td>The Y translation error induced by the combination of both steppers. (µm)</td>
</tr>
<tr>
<td>$S_{y}$</td>
<td>$S_{yn} + S_{yw}$</td>
<td>The Y scale error induced by the combination of both steppers. (ppm)</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>$\Phi_n + \Phi_w$</td>
<td>The wafer orthogonality error induced by the combination of both steppers. (ppm)</td>
</tr>
</tbody>
</table>

Table 3: Summary statistics for three wafers the Canon 2500i2 mix-and-match lot.

<table>
<thead>
<tr>
<th>Test Lot (1964 Measurements)</th>
<th>Mean</th>
<th>3 Sigma</th>
<th>Shapiro-Wilk W Value</th>
<th>W Test Prob. &lt; W</th>
<th>99.5% Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>X Data</td>
<td>-0.077</td>
<td>0.360</td>
<td>0.978</td>
<td>0.000</td>
<td>0.292</td>
</tr>
<tr>
<td>Y Data</td>
<td>0.006</td>
<td>0.300</td>
<td>0.988</td>
<td>0.574</td>
<td>0.267</td>
</tr>
</tbody>
</table>

Table 4: Comparison of three grid models for 2:1 field matching.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>2:1 Model</th>
<th>Narrow Field</th>
<th>Wide Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{gx}$</td>
<td>-50 nm</td>
<td>-50 nm</td>
<td>-32 nm</td>
</tr>
<tr>
<td>$T_{gy}$</td>
<td>15 nm</td>
<td>15 nm</td>
<td>21 nm</td>
</tr>
<tr>
<td>$S_{y}$</td>
<td>-0.27 ppm</td>
<td>-0.27 ppm</td>
<td>-0.27 ppm</td>
</tr>
<tr>
<td>$\Phi$</td>
<td>1.27 ppm</td>
<td>0.88 ppm</td>
<td>1.486 ppm</td>
</tr>
<tr>
<td>$S_{xn}$</td>
<td>-5.74 ppm</td>
<td>-0.51 ppm</td>
<td></td>
</tr>
<tr>
<td>$S_{xw}$</td>
<td>5.87 ppm</td>
<td>0.05 ppm</td>
<td></td>
</tr>
<tr>
<td>$\Theta_{gn}$</td>
<td>3.85 ppm</td>
<td>0.55 ppm</td>
<td></td>
</tr>
<tr>
<td>$\Theta_{gw}$</td>
<td>-3.69 ppm</td>
<td></td>
<td>-0.061 ppm</td>
</tr>
<tr>
<td>X Error ($\sigma$)</td>
<td>134 nm</td>
<td>134 nm</td>
<td>134 nm</td>
</tr>
<tr>
<td>Y Error ($\sigma$)</td>
<td>133 nm</td>
<td>133 nm</td>
<td>133 nm</td>
</tr>
<tr>
<td>X Residual ($\sigma$)</td>
<td>95 nm</td>
<td>113 nm</td>
<td>110 nm</td>
</tr>
<tr>
<td>Y Residual ($\sigma$)</td>
<td>126 nm</td>
<td>131 nm</td>
<td>130 nm</td>
</tr>
</tbody>
</table>
Table 5: Summary of 2:1 model coefficients for three wafers.

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Wafer 1</th>
<th>Wafer 2</th>
<th>Wafer 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{gx^*}$</td>
<td>-50 nm</td>
<td>-55 nm</td>
<td>-65 nm</td>
</tr>
<tr>
<td>$T_{gy^*}$</td>
<td>15 nm</td>
<td>17 nm</td>
<td>16 nm</td>
</tr>
<tr>
<td>$S_y^*$</td>
<td>-0.27 ppm</td>
<td>-0.33 ppm</td>
<td>-0.28 ppm</td>
</tr>
<tr>
<td>$\Phi^*$</td>
<td>1.27 ppm</td>
<td>0.93 ppm</td>
<td>0.79 ppm</td>
</tr>
<tr>
<td>$S_{xn}$</td>
<td>-5.74 ppm</td>
<td>-5.65 ppm</td>
<td>-5.78 ppm</td>
</tr>
<tr>
<td>$S_{xw}$</td>
<td>5.87 ppm</td>
<td>5.85 ppm</td>
<td>6.48 ppm</td>
</tr>
<tr>
<td>$\Theta_{gn}$</td>
<td>3.85 ppm</td>
<td>2.37 ppm</td>
<td>2.57 ppm</td>
</tr>
<tr>
<td>$\Theta_{gw}$</td>
<td>-3.69 ppm</td>
<td>-2.23 ppm</td>
<td>-2.40 ppm</td>
</tr>
<tr>
<td>X Error ($\sigma$)</td>
<td>134 nm</td>
<td>125 nm</td>
<td>126 nm</td>
</tr>
<tr>
<td>Y Error ($\sigma$)</td>
<td>133 nm</td>
<td>124 nm</td>
<td>126 nm</td>
</tr>
<tr>
<td>X Residual ($\sigma$)</td>
<td>95 nm</td>
<td>95 nm</td>
<td>96 nm</td>
</tr>
<tr>
<td>Y Residual ($\sigma$)</td>
<td>126 nm</td>
<td>121 nm</td>
<td>121 nm</td>
</tr>
</tbody>
</table>

Figure 1: Exploded view of 2:1 field overlay.
Step #1: Gather measured data points from the X-Y overlay metrology instrument.

Step #2: Using relationships of 2:1 matched fields, identify data point locations in both wide and narrow field coordinate systems.

Step #3: Identify a model of assignable sources of overlay misregistration error for both the narrow and wide field steppers.

Step #4: Identify inseparable composite coefficients for the identified wide and narrow field models.

Step #5: Develop a single model using the inseparable composite terms and the separable terms.

Step #6: Create a system of equations using least squares estimation techniques, fitting measured data to the model developed in step #5.

Step #7: Compute the residuals of the analysis by subtracting the estimated vector contributions at each point from the measured values.

*Figure 2:* Pictorial flow chart of the 2:1 field model algorithm.
Figure 3: Field layout for the 2:1 matching showing overlay measurement locations.

Figure 4: Cross sectional depiction of alignment and composite film stack at pad mask level.

Figure 5a: Ultratech 2244i wafer layout.

Figure 5b: Canon 2500i2 wafer layout.

Figure 6: Wafer layout for the Canon narrow field stepper.
Figure 7a: Histogram of X overlay error for the 2:1 field matching of the Ultratech 2244i to Canon 2500i2.

Mean = -0.077
3 Sigma = 0.360

Figure 7b: Histogram of Y overlay error for the 2:1 field matching of the Ultratech 2244i to Canon 2500i2.

Mean = 0.06
3 Sigma = 0.300
Figure 8a: Histogram of x residual overlay error for 2:1 model.

Figure 8b: Histogram of y residual overlay error for 2:1 model.

Figure 9a: Histogram of x residual overlay error for narrowfield model.

Figure 9b: Histogram of y residual overlay error for narrowfield model.
Figure 10a: Histogram of X residual overlay error for widefield model.

Figure 10b: Histogram of Y residual overlay error for widefield model.

Figure 11a: Histogram of X residual overlay error for 2:1 model and narrowfield magnification correction.

Figure 11b: Histogram of Y residual overlay error for 2:1 model and narrowfield magnification correction.