Image-based overlay target design using a grating intersection

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Abstract

Background: An overlay target design is essential before performing overlay metrology and has a great impact on overlay performance. In addition, accurate overlay metrology is required to achieve high product yields in semiconductor manufacturing. When asymmetry of the overlay target occurs, it is necessary to increase the area of the pattern existing in the target and stabilize the optical aberration for stable measurement. For this reason, we propose an image-based overlay target design that can secure a larger area compared with the existing overlay target and stabilize the optical aberration by overlapping and exposing the upper and lower patterns of the overlay target.

Aim: The effective area of the existing mark design is improved by proposing an overlay target and a measurement method used in image-based overlay measurement.

Approach: The proposed overlay target design is configured by arranging different marks orthogonally to the upper and lower layers, and different two-dimensional information can be inserted in the same area. When necessary, single-dimensional information desired by the user can be obtained through a technique called projection, and it has the advantage of using a larger effective area than the existing overlay target.

Results: Overlay can be measured using projected signal components, and the possibility and performance of the proposed target can be confirmed through simulation and test wafer. In addition, it was possible to bring about a 15% improvement in total measurement uncertainty performance compared with the existing advanced imaging metrology (AIM) target by taking a wider effective area.

Conclusions: An overlay target design is proposed to solve the technical problems of the existing overlay target design. The proposed overlay target has a method that is capable of minimizing the size of the overlay target while maximally maintaining the signal density, a way of reducing the influence of aberration, and various other advantages. In addition, the proposed method provides a design rule that breaks the “lower pattern and upper pattern must not overlap” framework.

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1 Introduction

An overlay refers to the vertical alignment (or misalignment) and overlay control between the circuit pattern manufactured in the previous and current layer by stacking circuit patterns in the semiconductor manufacturing process. As shown in Fig. 1, when each circuit pattern is generated (mainly in the photolithography and etching processes), open and short circuits that may
unintentionally occur between the patterns are created if it deviates from the required precise position. These defects (disconnection and short circuit) have to be measured with more precise vertical alignment as the line width of the circuit to be manufactured smaller. In other words, as the circuit pattern becomes smaller due to technological development, the required level of technology also increases. Because measurement becomes difficult with the existing technology, the overlay target must be developed in parallel with the development of the pattern miniaturization technology.

The overlay target must be refined as the circuit to be manufactured. The reason is that, as the size of the circuit pattern becomes smaller, a more accurate overlay can be measured as the overlay target pattern becomes smaller. As the technology of the circuit line width develops, it is necessary to minimize the size of the overlay target while maintaining the maximum signal density.2

The measurement results are influenced by optical design and technology because image-based overlay (IBO) obtains measurement data through an optical system. Currently, commercial optical systems focus only on optical axis alignment. As the semiconductor process becomes more complicated and the step height increases, it is difficult to measure the overlay in a simple optical axis alignment accurately. Therefore, it is necessary to establish a precise optical system from the H/W design stage by adjusting the optical axis and aberrations affecting the optical system performance, such as stockpiling alignment, coma, and distortion aberration. The aberration mentioned refers to the phenomenon that the light from one point does not gather at the next point through the optical system when forming the image, but the image is colored and distorted. The aberration can be divided into monochromatic aberration and color aberration. The color aberration comes from the dispersion characteristics of the lens medium, and monochromatic aberration comes from the geometric shape of the lens or mirror regardless of dispersion. Among them, five monochromatic aberrations, excluding chromatic aberrations, are called the five aberrations of the Seidel.3 As shown in Fig. 2, spherical and distortion aberrations greatly influence the overlay measurement. Spherical aberration is a phenomenon that occurs

![Fig. 1 The process of overlay error.](image)

![Fig. 2 Monochromatic aberration. (a) Spherical aberration and (b) distortion aberration.](image)
because the focus of the paraxial ray close to the optical axis is different from the focal point of the paraxial ray far from the optical axis. Distortion aberrations produce a pin cushion or barrel effect that does not match the exact image of the subject. Due to the monochromatic aberration effect, a difference between the outer and inner regions of the overlay target may occur, which may affect the measurement result of a delicate pattern.

To improve the productivity and yield of the semiconductor manufacturing process, the vertical stacking misalignment must be measured. At the same time, the photoresist is applied before the etching process, which generates a circuit in a complete form. This means that the object to be measured is still coated with a photosensitive material, so a probe (electron beam or UV) with high energy density cannot be used. Ultimately, as a prerequisite for nondestructive measurement, a probe (visible light) with low energy density should be used. Also, unlike the upper pattern layer, the lower pattern layer is patterned where the preprocessing is completed (etching process is completed). The signal density may deteriorate compared with the upper pattern layer. This paper proposes a new overlay target design to solve these technical problems. The proposed overlay target has a method capable of minimizing the size of the overlay target while maximally maintaining the signal density, a way of reducing the influence of aberration, and various other advantages.

The remainder of this paper is organized as follows: related works are described in the next section. In Sec. 3, the overlay target using a grid pattern is described. Section 4 proves the validity of the proposed target through experiments. Conclusions are provided in the final section.

2 Related Work

2.1 Conventional Overlay Target Design

Conventional overlay metrology is used at each step in the semiconductor manufacturing process to monitor and control one or more semiconductor layers. For example, overlay metrology is used to measure one or more characteristics of a wafer, such as the dimensions (e.g., linewidth, thickness, etc.) of features formed on the wafer during a semiconductor processing step; the quality of the processing step measures one or more characteristics. It can be determined by one such feature, including overlay error. Overlay measurement is generally a process of calculating how accurately the lower pattern layer and the upper pattern layer are aligned or how accurately patterns disposed on the same pattern layer are aligned.

The most commonly used designs in the field of overlay target are box in box (BIB) key and grating key (AIM). BIB Key is a target design that has been used traditionally and can improve the performance of overlay metrology in the case of the grating key. The theoretical basis is described in “Optimized Overlay Metrology Marks.” Figure 3 shows the most commonly used target designs in the field. The blossom key in Fig. 3 has the feature of being able to measure the overlay of multiple layers simultaneously with a single target, and the Auros key has the feature of being able to minimize the aberration error.

Patterned patterning layers form a semiconductor device on a semiconductor substrate or wafer. In a semiconductor manufacturing process, an overlay between previously patterned pattern layers and a current pattern layer to be patterned may be measured. The overlay is measured

![Fig. 3 Design step for the overlay target. (a) Box in box, (b) Auros, (c) AIM, and (d) blossom.](image-url)
independently for the previously patterned pattern layer and the current patterned pattern layer and is calculated using the overlay target patterns located in each pattern layer. Existing overlay targets should not have overlapping patterns to allow for independent measurements. Therefore, efficient management of the area of the overlay target patterns is required due to the size and overlapping requirements. In addition, a high signal density is needed to improve the accuracy of the overlay. Because the high signal density is proportional to the area where the pattern is inserted, it can be seen that the size and design of the target and the precision of the overlay measurement have a close relationship. In the end, the density and intensity of the signal inserted into the pattern should be considered to be essential factors.

Figure 4 is a method to maximize the density of the overlay target. The bar and space are inserted at the minimum interval in both the $X$ and $Y$ axes. An overlay target made based on such a method (grating pattern) is an advanced imaging metrology (AIM) target. In addition, the grating pattern is also used for phase shift monitoring\(^8\) or to align mark.\(^9\) The AIM target is a design based on the grating pattern and is currently the most used. However, in the case of the AIM target, the lower and upper patterns are inserted at different positions to satisfy the overlapping requirements. For this reason, problems may arise due to optical aberrations, and because the target is inserted by dividing the $X$-axis and $Y$-axis, there is room for optimization in terms of density. After all, if the information (content) of the overlay target is increased, the influence of random noise on the overlay measurement can be minimized. Random noise causes overlay inaccuracy, and various studies have been conducted to improve it.\(^10\)–\(^12\) There are also several research studies for evaluating and minimizing target noise.\(^13\)–\(^15\) This paper proposes a new overlay target to solve these two problems.

2.2 Conventional Overlay Measurement

Overlay measurements are based on horizontal and vertical position measurements of known patterns. First, to present a simple explanation, the horizontal position measurement of 1-D Pattern $g_0(x)$, known from a two-dimensional image, is described. The vertical position measurement can be performed similarly. In this case, it can be assumed that the measurement is performed independently for all image rows and returned to the average pattern location estimation result. The periodic pattern of the line is expressed as

$$g(x, y) = g_0(x) + n_s(x, y), \quad (1)$$

where $g_0(x)$ is a one-dimensional pattern repeated on all lines and $n_s(x, y)$ is the spatial noise of the wafer. Equation (2) gives the pattern in each row of the image acquired by the camera

$$f(x) = g * h + n_t, \quad (2)$$

where $h$ is the total point spread function composed of optical and camera point spread functions and $n_t$ is the temporal noise of the camera output. All signal noise terms are assumed to be filtered and are supposed to be normally distributed noise.

Figure 5 shows the process of measuring the horizontal position of the BIB and AIM target. Based on the selected area, the pattern location is estimated using the correlation method in all rows. All rows are performed independently, and the average pattern location estimate is returned as a result. The correlation method refers to an algorithm that finds the peak value...
by analyzing the correlation of two signals, calculating the correlation coefficient values, and interpolating the values. For example, in Fig. 5, the right multi-region is selected as a comparison target based on a single area of BIB. The number of multiple areas is taken as the search range. The correlation coefficient of the data in the reference area and the data in the multiarea is calculated. After that, the optimal location is found by interpolating the correlation coefficient values.

Lithographic metrology tasks, such as overlay measurements, typically require that the pixel size of the image be much larger than the instrument’s desired accuracy. Interpolating the image data before applying the measurement algorithm enables accurate measurement but increases the amount of data to be processed and requires a lot of computational resources. In the end, the peak point is found by interpolating the values after calculating the correlation coefficient to solve the problem

\[
\sigma^2 = \frac{2 \times E}{N} \quad \beta^2 = \frac{\int_{-\infty}^{\infty} \omega^2 |F(\omega)|^2 \, d\omega}{\int_{-\infty}^{\infty} |F(\omega)|^2 \, d\omega} \Rightarrow \text{var} (\hat{\theta}) = \frac{1}{2\beta^2 \cdot T \cdot \text{SNR} \cdot B}.
\]

Assuming that \(\hat{\theta}\) is an estimate of the pattern location \(\hat{\theta}\) of a noise-free one-dimensional signal \(f(x)\), the variance of \(\hat{\theta}\) is given as in Eq. (3). The formula means the minimum value by the Cramer–Rao lower bound.\(^{16,17}\) For example, when there is a certain estimator, the variance cannot be lowered below a certain value by the Cramer–Rao lower bound. In the end, the distribution of pattern location estimates is derived from all measurements, and the optimal parameter is found based on the Cramer–Rao lower bound, a statistical tool\(^{18,19}\)

Fig. 5 Horizontal position measurement (pattern location estimator). (a) BIB measurement and (b) AIM measurement.

where \(E\) is the signal’s energy, \(N\) is the spectral density of the noise, \(\beta\) is the effective bandwidth of the signal, \(t\) is the signal length, \(B\) is the noise bandwidth, and \(\text{SNR}\) is the signal to noise ratio.
\( E \) is equal to the average signal power divided by the signal length, and \( N \) is the noise power divided by the noise bandwidth. Therefore, the variance of the final \( \theta \) can be expressed as the right-side expression of Eq. (4). This formula shows that precision is a function of the signal and noise bandwidth, SNR, and signal length.

\( f(x) \) in Eq. (2) is affected by spatial and temporal noise, and in both cases, the optical system determines the effective bandwidth (\( \beta \)) of the signal. The upper bound of \( \beta \) is determined by diffraction and can be approximated by the reciprocal of the Rayleigh resolution distance given by Eq. (5), where \( \lambda \) is the optical wavelength and NA is the numerical aperture of the optical system

\[
\delta = \frac{0.61 \cdot \lambda}{\text{NA}} \Rightarrow \beta_{\text{max}} = \frac{2\pi \cdot \text{NA}}{0.61 \cdot \lambda}.
\]  

Equation 6 for the standard deviation of the pattern location is obtained through Eqs. (4) and (5)

\[
\text{std}(\hat{\theta}) \geq \frac{0.61 \cdot \lambda}{2\pi \cdot \text{NA}} \sqrt{\frac{1}{2 \cdot \beta \cdot \text{SNR} \cdot B}}.
\]  

Finally, Eq. (6) confirms that the variance decreases when \( T \) is increased while keeping all other factors constant. The same result should be obtained with estimation noise if repeated for several image rows. When averaging the measurement values, the precision increases by the square root of the number of independent measurements. In this way, measuring as many of the number of rows (\( L \)) of the selected area as possible is considered for each of the two noises

\[
\text{std}(\hat{\theta}) \geq \frac{0.61 \cdot \lambda}{2\pi \cdot \text{NA}} \sqrt{\frac{1}{2 \cdot \beta \cdot \text{SNR} \cdot B \cdot L}}.
\]  

First, in the case of temporal measurement noise, the number of independent measurements is \( L \), so the standard deviation is expressed as Eq. (7)

\[
\delta = \frac{0.61 \cdot \lambda}{\text{NA}} \Rightarrow L_{\text{eff}} = \frac{L}{\delta}.
\]  

In the case of the following spatial measurement noise, the number of independent measurements cannot be \( L \) because the optical point spread function blurs the noise. Therefore, the number of independent measurements is expressed by Eq. (8). Here, \( L_{\text{eff}} \) represents the number of independent measurements, and \( \Delta \) represents the wafer vertical sampling interval. Additionally, noise bandwidth (\( B \)) is interpreted as the inverse of optical spatial resolution \( \sigma \). After all, the standard deviation of spatial measurement noise is calculated as

\[
\text{std}(\hat{\theta}) \geq \left( \frac{0.61 \cdot \lambda}{2\pi \cdot \text{NA}} \right)^2 \frac{1}{2\pi} \sqrt{\frac{1}{2 \cdot \beta \cdot \text{SNR} \cdot L \cdot \Delta}}.
\]  

Finally, it can be seen that the method to increase the precision of the overlay target through the standard deviation equations for the two noises is to reduce the wavelength and increase the information content (effective bandwidth) of the signal, the spatial region \((T, L)\) and the SNR of the signal.\(^{18,19}\) This paper proposes a target design that increases the spatial region \((T, L)\) of the signal and offers a precision improvement method.

### 3 Proposed Overlay Target Design

#### 3.1 Grating Intersection (GI) Key

The newly proposed target design inserts intersecting patterns into the upper and lower layers using a grid pattern. The grid pattern was made so that the upper and lower parts intersect, and it was called the grating intersection (GI) key.
The GI key can reduce the size of the overlay target according to the increasingly delicate semiconductor circuit pattern by arranging different marks orthogonally on the same plane, and it can solve the problems of the existing overlay target due to optical aberration. The GI key is a target used for IBO measurement and can use space more effectively than the existing AIM target. The GI key can be designed in various ways, such as methods using different pitches or different sizes of critical dimension (CD), examples of which can be seen in Fig. 6.

The GI key is designed by inserting some gratings patterns in different layers orthogonally, unlike previous grating patterns.

Figure 7 shows the design of the GI key for measuring the overlay. The aberration information of each layer was arranged the same, and unnecessary regions for suppressing the effect of wavelength interference between the upper and lower patterns were removed. Therefore, the size of the overlay target can be reduced, and the density and area of the signal can be broader than that of the existing overlay target.

Current overlay measurement algorithms use projection to obtain single-dimensional signal data. As a GI Target characteristic, periodic patterns in the same direction as projection
disappear, and only periodic patterns in orthogonal directions remain. Using these phenomena, a periodic pattern of the $X$-axis and the $Y$-axis can be intersected in the same area, and the amount of change between the $X$-axis and the $Y$-axis can be measured using this data. Ultimately, two-dimensional information of the $X$-axis and $Y$-axis is inserted in the same area to measure the overlay. The desired dimensional information can be obtained at a user’s desired point of time through a projection process. Through this process, the same area can be used more effectively. The signal density can be increased. Figure 8 shows the process of obtaining desired dimension information through the project.

Although the grid pattern has many advantages, it is not easy to use in an actual lithography process because of cross-interference. Cross-interference is a phenomenon that occurs when an overlay target is exposed and the shape is deformed by intersecting patterns that affect the surroundings. For this reason, a modified form is used instead of using the grid pattern as it is.\(^5\)\(^-\)\(^7\)

Figure 9 is an overlay target designed to suppress cross-interference, and it is designed by filling in the intersecting points with blanks to eliminate cross-interference. The design of inserting an intersection pattern on another floor like the GI key is an improvement that puts an intersection pattern on the same floor as the blossom key. Putting the intersection pattern on the same floor has the disadvantage that the window definition becomes complicated for removing the cross-interference. In contrast, placing the intersection pattern on different floors does not need to consider the cross-interference, so the window definition is simplified. In a typical semiconductor photolithography process, pattern distortion occurs due to light diffraction and interference, and an optical proximity effect occurs in which the distorted image is formed at the edge depending on the fineness of the size and spacing of the pattern. A bar-shaped overlay target is used to minimize the optical proximity effect, and it is possible to reduce the overlay measurement error due to edge shape distortion. The overlay target design in this paper uses grating intersection and applies an individual bar pattern photolithography/etching process to upper/lower layers, thereby minimizing the pattern distortion compared with existing lattice-shaped targets and improving the patterning precision.

Fig. 8 GI Pattern projection. (a) Lower left, upper right: upper (red) measures $x$-axis change, and lower (blue) measures $Y$-axis change. (b) Upper left, lower right: upper (red) measures $Y$-axis change, and lower (blue) measures $X$-axis change.
3.2 Updated Grating Intersection Target Design

The GI Key has various advantages as described, but it also has disadvantages. The disadvantage is that, as the signal density of the upper pattern increases, it is difficult to check the signal data of the lower way. A GI key having a different number of bars is proposed to solve this problem. The solution is to set the pitch to more than twice the optical resolution, so the upper pattern can observe the lower pattern signal.

Figure 10 shows the improvement process of the GI overlay target proposed in this paper, and the GI Key can be used according to the situation.

The updated grating intersection target is thought to obtain similar signal data to the existing overlay target because it takes a broader signal area instead of lowering the signal density of the upper pattern. In addition, the lower pattern has the advantage of using a wider signal area while having the same signal density as the existing target. It can increase the signal density of the lower pattern instead of lowering the signal density of the upper pattern. For this reason, it is judged that the problem of lowering the signal strength of the lower pattern can be solved. However, this paper proposes a method that is useful when the signal of the lower pattern is not visible or the signal strength is poor when using the GI key and does not separately prove the updated grating intersection target. Therefore, the updated grating intersection was not covered in this experiment.
3.3 Advantages of the Proposed Overlay Target

Compared with the existing overlay target, the proposed target has three advantages.

First, as shown in Fig. 11, an unnecessary area due to the existing optical proximity effect is removed so that the effective area of the signal is increased, and the space can be effectively used by inserting two-dimensional information in the same area.

Second, as shown in Fig. 12, in the case of the conventional overlay target, there is a possibility that the optical aberration may be different due to the difference in spatial positions of the lower pattern and the upper pattern. However, in the case of the proposed GI target, the problem of different optical aberrations can be solved because the lower pattern and the upper pattern have the same spatial location.

Third, as shown in Fig. 13, in the case of the existing overlay target, eight regions must be selected and calculated to calculate the overlay $X$-axis information and the overlay $Y$-axis information.

Fig. 11 Effective use of the area. (a) Inner horizontal and outer vertical combination and (b) outer horizontal and inner vertical combination.

Fig. 12 Optical aberration improvement. (a) Optical aberrations of inner and outer are different and (b) optical aberrations of inner and outer are the same.
information. Still, only four areas can be selected and calculated in the case of the proposed GI target. Therefore, the interface can be simplified from the point of view of the user who measures the overlay.

4 Experiments

4.1 Testing Environment and Methods

Experiments are conducted in two ways: target verification using simulation and target verification in actual equipment using a test wafer.

The simulation used RSoft Tool (Synopsis, Inc.), to which the FDTD and RCWA algorithms were applied to examine the possibility of measuring the GI target S/W.\textsuperscript{20-22} Input variables of RSoft tool are divided mainly into simulation structure (laminated structure, lattice structure, and structural analysis area), material information (refractive index, etc.), and incident light characteristics (wavelength, angle, and polarization). As shown in Fig. 14, the simulation structure was designed as an arbitrary structure.

![Fig. 13 Simplified user interface. (a) Selection of eight areas and (b) selection of four areas.](image)

![Fig. 14 Structure of GI target simulation.](image)

| Layer | Material | Refractive index | Thickness(nm) |
|-------|----------|------------------|---------------|
| 4     | Resist/Air | 1.5146           | 100           |
| 3     | SiO₂     | 1.5146           | 200           |
| 2     | Tungsten | 1.5146           | 150           |
| 1     | SiO₂     | 1.5146           | Infinity      |
The total area of the GI Target is $24 \times 24 \, \mu m^2$, and the pitches of the two patterns are 2 and $4 \, \mu m$, respectively. The bar line width is $1 \, \mu m$. For NA information, input is set to 0.3, and output is set to 0.7. Additionally, the size of 1 pixel in the simulation result is 80 nm.

To test the proposed target in actual equipment, two test wafers were produced (Test1, Test2). The proposed GI key and comparison target keys were exposed in the test wafer, and measurements were carried out using the Aurostech IBO Tool, an overlay measurement tool. To verify the overlay performance, a simple test structure was selected to minimize the influence between the layers, and then the practical layer was applied. Figure 15 shows a cross-section of the test structure. AIM ($22 \times 22 \, \mu m$), GI ($22 \times 22 \, \mu m$), and small GI ($16 \times 16$) were compared for measurement. The two wafers were repeatedly measured five times and tested. There were 185 sites on one wafer, and five overlay targets were inserted in each area. All three targets (AIM, GI, and small GI) were tested under the same conditions. Metrology performance of the overlay is generally evaluated based on random error contributions such as precision and TIS variability, and this experiment was also evaluated based on these indicators of the instrument.

### 4.2 Simulation

As shown in Fig. 16, a simulation result in which the current layer of the GI target was fixed was created. Then the previous layer was artificially shifted for the evaluation of the overlay consistency. The overlay target created by simulation consists of patterns drawn in current and previous layers. In the case of the current pattern, the pitch is inserted at $4 \, \mu m$, and in the case of the previous pattern, the pitch is inserted at $2 \, \mu m$. Using each existing pattern, the kernel’s center of gravity (COG) is calculated and the overlay between the two layers is measured. In this paper, the word registration is used instead of COG.

![Fig. 15 Structure for the test cross-section and wafer.](image)

![Fig. 16 Review samples for the overlay measurement.](image)
The method of overlay measurement calculates the top layer’s registration $X$ and the bottom layer’s registration $X$ by performing vertical projection on each area and then calculates the overlay $X$ value using the difference. As shown in Fig. 17, the horizontal projection can be performed to calculate the overlay $Y$ value in the same way.

As mentioned in the experimental environment, 1 pixel of the test set created by simulation is 80 nm. As shown in Fig. 18, the current layer has a registration value of 0.1 nm or less because it is fixed. This is equivalent to saying that it can have an error of 0.1 nm, and it is a number that occurs under the influence of measurement and simulation design. It can be seen that the registration value of the preferential layer increases according to the step.

This experiment confirmed that the simulation results are typically generated through this experiment. At the same time, it can be assured that the change values are accurately reflected in the current layer and previous layer. In addition, it was possible to confirm the possibility of measuring the registration value of the GI key through the S/W algorithm.

![Fig. 17](image_url) Method of the overlay measurement. (a) Vertical projection and (b) horizontal projection.

![Fig. 18](image_url) Registration simulation results of the overlay measurement.

| Step  | Interm. Cur. $X$ | Edge Cur. $X$ | Interm. Pre. $X$ | Edge Pre. $X$ |
|-------|-----------------|--------------|-----------------|---------------|
| 0nm   | 0.09            | -0.00036     | -0.00192        | 0.0164        |
| 1nm   | 0.06616         | -0.00938     | 1.06776         | 1.08164       |
| 2nm   | 0.0892         | 0.04512      | 1.92976         | 1.93356       |
| 3nm   | 0.0696         | 0.01288      | 2.08608         | 3.00994       |
| 4nm   | 0.07816        | 0.00664      | 3.97888         | 4.02372       |
| 5nm   | 0.09424        | 0.04552      | 4.96336         | 5.00208       |
| 10nm  | 0.07784        | 0.008        | 10.04135        | 10.15066      |
| 20nm  | 0.06672        | -0.0238      | 20.04728        | 20.09536      |
| 30nm  | 0.0792         | 0.00248      | 30.10712        | 30.06728      |
| 40nm  | 0.08168        | -0.00068     | 39.99176        | 40.02816      |
| 50nm  | 0.10976        | 0.00936      | 49.88854        | 49.98784      |
As a result of measuring the overlay using the regulation value, the shift in nanometer units can be measured with the current target design and algorithm. As shown in Fig. 19, the overlay value increased as the amount of shift increased, and the overlay value of 50-nm step was 49.78008, theoretically representing an error value of 50 and 0.22 nm. The high accuracy of the real value of the actual simulation result was confirmed. When testing by converting the input data to an edge, a more accurate value was obtained at 0.16 nm, but there is little difference.

### 4.3 Device Experiment

The standard evaluation of the capabilities of the overlay metrology tool mainly uses total measurement uncertainty (TMU), which includes precision, TIS variability, and tool matching. However, as the overlay control requirements become very stringent, it does not guarantee that a small TMU will meet the overlay metrology budget because some measurement errors are not taken into account in the TMU. One of the measurement errors is that precision and TIS variability appear to be relatively smaller than tool matching, so the TMU that uses the three values combined has no choice but to dominate the tool matching parameter. For this reason, an additional comparative experiment with the AIM target is conducted in addition to the TMU comparison.

In addition, the performance of overlay metrology of TMU should be mainly evaluated based on random errors such as precision and TIS variability. However, since precision and TIS variability appear relatively smaller than tool matching, TMU using three values combined is used for tool matching. Therefore, this paper alleviated this problem using TIS mean instead of tool matching.

Because the experiments are measured using actual test wafers, it is very difficult to control and measure minute imperfections. In general, all patterns have microscopic imperfections inserted during exposure. This “fine” means a small number of nanometers or less, and because it is physically controlled, this microscopic imperfection can affect the precision of different targets. This can alleviate the imperfection that is generated by the design aspect of the target, and the AIM target used in the current process can measure by minimizing the imperfection that occurs in the exposure and optical system. In the end, the new target can check the uncertainty and measurability of the target through a comparison between the verified existing targets.

The experimental method was measured and compared with AIM, GI, and small GI targets existing in the actual test wafer. A comparative analysis was also conducted through the performance aspect of the target, matching with the existing AIM target, and the target quality metric.
As shown in Fig. 20, the GI target has an advantage of about 15% compared with the AIM target in terms of TMU. In addition, the small GI target (16×16 μm) achieved an equivalent TMU with 53% of the area compared with the AIM target (22×22 μm).

However, it is difficult to conclude that a GI target is a target with better performance than an AIM target based on TMU performance alone. Through additional experiments, it is possible to confirm the possibility of the GI target rather than proving that it shows better performance than the AIM target.

As shown in Fig. 21, it was confirmed that 96% to 99% of matching values could be obtained due to checking the matching of the AIM key and GI key under the same conditions. The matching value gives the similarity between the data measured by the AIM key and the data measured by the GI key. Precision and accuracy of overlay metrology have different influences for each overlay target or process. Therefore, a method of indexing the quality of the overlay target, which is the measurement target, is required, and the registration inaccuracy index (RII) or Q-merit is used as the index. RII compares different measurement algorithms to index the quality of the overlay target. The exponentiation method uses the difference between the brightness-based...

| Key type | Key size (μm) | TMU (nm) | Overlay REG 3σ (nm) | TIS mean (nm) | TIS 3σ (nm) | Precision RMS (nm) |
|----------|---------------|----------|---------------------|---------------|-------------|------------------|
| AIM      | 22x22         | 0.24     | 0.14                | 19.80         | 0.01        | 0.23             |
| GI       | 22x22         | 0.16     | 0.15                | 19.97         | 0.03        | 0.12             |
| Small GI | 16x16         | 0.23     | 0.19                | 19.88         | 0.04        | 0.18             |
| AIM      | 22x22         | 0.21     | 0.19                | 13.25         | 0.08        | 0.18             |
| GI       | 22x22         | 0.16     | 0.16                | 13.83         | 0.04        | 0.13             |
| Small GI | 16x16         | 0.21     | 0.18                | 13.58         | 0.05        | 0.17             |

**Fig. 20** Performance of GI key. (a) AIM target, (b) GI target, and (c) small GI target.

**Fig. 21** Matching of AIM key and GI key (same environment).
measurement algorithm result and the second derivative-based measurement algorithm. In general, the RII value increases in the high-level difference (more noise) layer than in the low-level difference (low noise) layer, and the difference between measurement algorithms also increases. That is, the RII index is used as a method to measure robustness in the measurement algorithm, and a high value means that the possibility of inaccurate measurement in terms of the algorithm increases. For example, if there is no overlay mark imperfection, similar values will appear even if different algorithms are used, and if there is overlay mark imperfection, there will be differences in the values of different algorithms. As shown in Fig. 22, the GI target is more robust to overlay mark imperfection than the AIM target because, in the case of the proposed GI target, the lithography pattern is simpler than that of the AIM target, so overlay mark imperfection is expected to occur less. Because the AIM target has a long bar and a large number of bars, it can be inferred that the probability of occurrence of imperfection is high.

Figure 23 shows the formula for calculating the standard deviation of the minimum estimator through CRLB. This formula proved that as the spatial region \((T, L)\) increases, the performance of precision can be increased. Based on this formula, the approximate effective area can be calculated based on the length and number of bars in the target, and the GI Key has a higher effective area than the AIM Key based on the same key size.
5 Conclusion

The experiment confirmed that the practical use of the grating intersection target and the accurate overlay measurement of the stacked vertical alignment are possible.

In addition, performance was improved by up to 15% compared with the most commonly used AIM target. As a result, the spatial region \( L \) was used more widely, and this had the effect of reducing the imperfection of the overlay target. However, in the experimental results, the performance of precision was lower or similar to that of the AIM target. Theoretically, a GI target with a large area should have a higher standard deviation than an AIM target, but an error occurs due to the overlapping area of the GI target. The overlapping area of the GI target has meaningful information because, although the lower film quality and the upper film quality exist on the same spatially plane, a constant value, not a random value, is always generated because they are located in completely different spaces in terms of a three-dimensional structure.

After all, the pattern created in the overlapping area is not noise, but an interference phenomenon generated in each layer, and this interference is a target of measurement because it can be a valid signal. Currently, this area is not utilized properly, so the same performance of precision is shown even if a large area is used. In future work, additional research is needed to make good use of this overlapping area, and through this, a more improved GI target needs to be developed.

The purpose of the GI key is to use an effective area that is as wide as possible, and it has the advantage of maintaining performance while reducing the size of the target. As mentioned in the introduction, as the circuit patterns of semiconductors become smaller, the size of the overlay target must also be minimized. In a future study of IBO measurement research, we plan to make the overlay target smaller. Currently, as the target becomes smaller, the pattern spacing decreases. And studies for viewing the spacing of patterns that cannot be considered by optical resolution are being conducted.\(^{25-28}\) In addition, there is research\(^{29,30}\) to reduce TIS using machine learning to improve measurement performance, and research to apply artificial intelligence to semiconductor processes will be an important field for overlay measurement in the future.

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