High Throughput Polarization Imaging for Defocus and Dose Inspection for Production Wafers

Gang Sun, Eugene Onoichenco, Yonghang Fu, Yongqiang Liu, Ricardo Amell,
Casey McCandless, Rajasekar Reddy, Gidesh Kumar, Max Guest
Rudolph Technologies, Flanders, NJ USA

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ABSTRACT

Advances in lithography create a unique challenge for process window control with defect inspection tools. As the technology moves towards smaller line widths and more complicated structures, the sensitivity requirements for some process defects become higher, such as defocus and dose defects at 50 nm or lower technology nodes. Currently, automated macro inspection tools are used to detect a wide range of macro defects in the litho area such as coating defects, particles, and scratches, as well as the process defects. Most tools, however, cannot satisfy the new sensitivity requirements for the process defects while maintaining their current inspection capability for other defects. Rudolph Technologies approaches this challenge by integrating a unique polarization-imaging configuration, which enhances detection of defocus and dose defects without sacrificing the existing capability to detect other types of macro defects. The improved inspection system has demonstrated high sensitivity for defocus and dose defects on production wafers at multiple process nodes at high throughput.

INTRODUCTION

Reflectivity change caused by focus or dose errors has long been used to detect these defects by visual inspection in the lithography area. Experienced inspectors can maximize the defects signature by looking at the wafer at a specific orientation using a specific light source. However, the inspection is prone to human error and the sensitivity is limited.

Many automated macro inspection tools have been developed to replace human inspectors for yield improvements[1], and are designed to image the whole wafer at high throughput and classify defects in real time. These macro tools can detect a wide range of pattern and resist defects using broad-spectrum illumination. In other cases the tools have been optimized to detect the specific signatures of defocus and dose defects at the expense of detecting other types of lithography defects.

Recent developments in optical scatterometry and ellipsometry for CD metrology revealed the physics of the reflection change caused by focus and dose errors[2,3]. Defocus and dose defects change the shape of the developed circuitry, such as the pitch, sidewall angle, and height of a repeating structure. The reflection coefficients of the structure are related to the geometry changes, as well as the properties of other film layers, and it is a function of wavelength, polarization, and angle-of-incidence. Many optical metrology tools today measure some of the critical dimensions such as pitch and sidewall angle of engineered structures based on this principle.

The polarization dependency of the reflection coefficients of defocus and dose defects, learned from CD metrology with scatterometry and ellipsometry, is the key to improving inspection sensitivity. Rudolph integrated a unique polarization-imaging configuration, which enhances the detection sensitivity of polarization-dependent defects (such as defocus) without sacrificing the existing capability to detect other types of macro defects. This is achieved without affecting the inspection tool's high throughput. Demonstrations have shown the defocus sensitivity improvement on production chips as well as on engineered targets.

A NEW CONCEPT OF POLARIZATION IMAGING

The goal of an inspection tool is to identify all of the key defects without false alarms as fast as possible on all areas of the wafer. The approach here is a polarization imaging system as shown in Fig.1. Illumination light is artificially polarized at an optimal state for the critical defects of interest. The light changes its polarization state upon reflection from the targets. Then, an imaging system with an analyzer captures the information at selected wavelengths or spectrum ranges at high throughput. The illumination is polarized elliptically in general, and linearly in its simplest case. This polarization state and the analyzer angle are optimized for the key defects during the recipe setup, in which reflectometry and ellipsometry information of the key defects are measured. Other practical considerations, such as the signal-to-noise ratio of the imaging system, are used to select the optimal angle. One wafer with known defects is needed to set up the recipe, and all of the subsequent wafers will be inspected at the fixed polarization configuration with high throughput imaging.

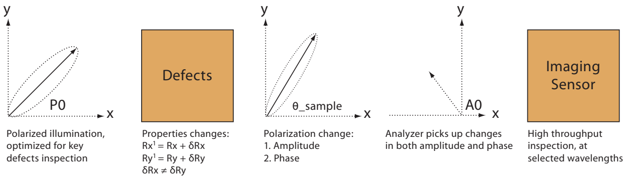

Figure 1 - Concept illustration on polarization imaging for defects inspection

Polarization dependent targets, such as defocus and dose defects, will have changes in the reflection coefficients compared to the nominal or background locations, as illustrated in Fig.2. In general, the amplitude and phase of the light will both change correspondingly upon reflection. Visual inspectors and traditional imaging systems pick up the total amplitude change only, but not the phase change. With an analyzer correctly oriented in the optimized direction, the system will pick up both the amplitude and phase information, increasing the relative sensitivity to the polarization dependent defects.

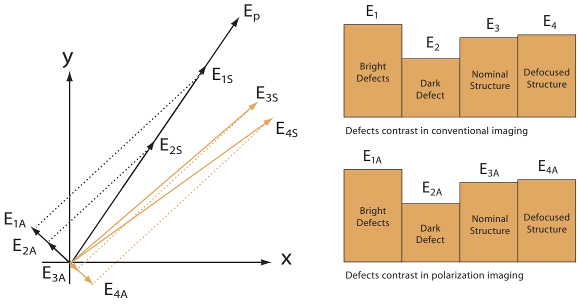

Figure 2 - Inspection sensitivity improvement for polarization dependent defects

As shown in Fig.2, assume the key targets for inspection are bright defects, dark defects, defocus structures and corresponding nominal structures. Linearly polarized illumination is used, and the incident electric field is EP. Assume the reflection coefficients of the bright and dark defects are polarization independent. The reflected fields of the bright and dark defects (E1S and E2S) will be in the same direction of EP, with amplitude ratio E1S/E2S determined by their reflection coefficients. The ratio of the fields after the analyzer, E1A/E2A, will be the same as E1S/E2S, independent to the cross angle between the polarizer and the analyzer. Assume the illumination intensity has a wide dynamic range, and can be changed with the change of the cross angle, such that the bright and dark defects will have about the same contrast and signal-to-noise-ratio in the captured images.

Assume the reflection coefficient of the nominal structure is polarization dependent, and the reflected light (E3S) will have its polarization rotated to a certain angle away from EP. Light reflected from the defocused structure E4S changes only slightly in amplitude and angle from E3S when the amount of defocus is small. Hence, the fields will project on the analyzer. In conventional imaging methods, only the amplitude difference will become the contrast in the image as the defects signature. In polarization imaging, when the analyzer is oriented at a correct angle, as in Fig.2, the defocus contrast will increase substantially, E4A/E3A >> E4S/E3S, while the contrast for other polarization independent defects will remain the same as above.

Generally, for an imaging system, each pixel on the sensor collects lights from all points of the effective area (or volume) of the light source, which associate with a range of incident and azimuth angles. The imaging system can be set up at normal or oblique angles. The resulting image is integration of all rays and all wavelengths passing through the polarization system.

INSPECTION ON DEFOCUS AND DOSE DEFECTS

Let's study the signature of defocus and dose defects in a system with linear polarization system, as described above, to identify the best polarization angles for their inspection. Assume Jones matrix, $\Re = \begin{pmatrix} r_{xx} & r_{xy} \\ r_{yx} & r_{yy} \end{pmatrix}$, represents the reflection coefficients of the nominal structure. The matrix elements are complex variables that depend on the geometry structure and the material properties of the target. It is also a function of the wavelength, incident angle, azimuth angle, and other parameters of the system. Defocus and dose defects change the profile of the developed film structure in lithography, which then changes the optical properties of the film structure, and therefore the reflection coefficients in $\Re$

The cross angle $P - A$ is fixed between the polarizer and analyzer to maintain the same contrast and signal-to-noise ratio of polarization independent defects. The polarizer and the analyzer are then rotated at the same time. The intensity of each ray after the analyzer is modulated with $P + A$ as,

$$
\begin{aligned}
(1)\qquad & I_A = I_A^0\left(1 + C_2\cos(P+A) + S_2\sin(P+A) + C_4\cos(2P+2A) + S_4\sin(2P+2A)\right) \\
& I_A^0 = I_P\left|\frac{r_{xx}+r_{yy}}{2}\cos(P-A) + \frac{r_{xy}-r_{yx}}{2}\sin(P-A)\right|^2 + \frac{I_P}{2}\left|\frac{r_{xx}-r_{yy}}{2}\right|^2 + \frac{I_P}{2}\left|\frac{r_{xy}+r_{yx}}{2}\right|^2 \\
& C_2 = \frac{4\,\mathrm{Re}(k_1)}{2+|k_1|^2+|k_2|^2}, S_2 = \frac{4\,\mathrm{Re}(k_2)}{2+|k_1|^2+|k_2|^2}, \\
& C_4 = \frac{|k_1|^2-|k_2|^2}{2+|k_1|^2+|k_2|^2}, S_4 = \frac{4\,\mathrm{Re}(k_1k_2)}{2+|k_1|^2+|k_2|^2}, \\
& k_1 \equiv \frac{r_{xx}-r_{yy}}{(r_{xx}+r_{yy})\cos(P-A)+(r_{xy}-r_{yx})\sin(P-A)}, \\
& k_2 \equiv \frac{r_{xy}+r_{yx}}{(r_{xx}+r_{yy})\cos(P-A)+(r_{xy}-r_{yx})\sin(P-A)}.
\end{aligned}
$$

These equations are similar to standard ellipsometry equations[4], but concentrate on capturing the difference between the reflection coefficients (r_{xx} & r_{yy}) in k_1, and the off diagonal terms (r_{xy} & r_{yx}) in k_2. The geometry changes in film structures from defocus or dose defects are much more in one direction than the other. The corresponding changes in the reflection coefficients therefore are not uniform. When illumination and imaging of the system is configured with the normal angle of incident, isotropic multilayer film structures become polarization independent, $r_{xx} = r_{yy}$, $r_{xy} = r_{yx} = 0$. This helps the tool single out polarization-dependent defects, such as those from focus and dose change.

For some structures, such as line structures on isotropic materials, the off-diagonal terms are zero ($r_{xy} = r_{yx} = 0$) when we select certain reference direction of the polarization. The intensity can be simplified as

$$
\begin{aligned}
(2)\qquad & I_A = I_A^0\left(1 + C_2\cos(P+A) + C_4\cos(2P+2A)\right) \\
& I_A^0 = I_P\left|\frac{r_{xx}+r_{yy}}{2}\right|^2\cos^2(P-A) + \frac{I_P}{2}\left|\frac{r_{xx}-r_{yy}}{2}\right|^2 \\
& C_2 = \frac{4K\cos\Delta}{2+K^2}, C_4 = \frac{K^2}{2+K^2}, \\
& D \equiv Ke^{i\Delta} \equiv \frac{r_{xx}-r_{yy}}{r_{xx}+r_{yy}}.
\end{aligned}
$$

The first part of the constant term I^O_A acts as polarization independent targets when $r_{xx} = r_{yy}$. The second part is independent of $P - A$, and it weights more when $P - A$ is close to 90°. When $P - A$ is fixed, we can measure the target intensity at different angles of $P + A$, as in standard ellipsometry, and fit it for C_2 and C_4. Then D, the normalized difference between the reflection coefficients, can be derived as

$$
(3)\qquad D \equiv Ke^{i\Delta} \equiv \frac{r_{xx}-r_{yy}}{r_{xx}+r_{yy}},\quad K = \sqrt{\frac{2C_4}{1-2C_4}},\quad \cos\Delta = \frac{C_2}{4}\sqrt{\frac{2}{C_4(1-2C_4)}}
$$

The geometry changes in the structure from the defocus or dose defects, will change D correspondingly. Reverse data analysis may be used to measure the critical dimensions.

For inspection purposes, the most sensitive polarization angles (P and A) must be found for the small change of r_{xx} and r_{yy}. After the measurement of D with a standard ellipsometry method, the shape of I_A can be calculated and the location with the highest slope (derivative of I_A relative to P and A) can be identified, which is the theoretically optimized polarization configuration for the normalized difference D. For specified geometry change, such as sidewall angle, caused by defocus or dose defects, the optimized configuration for its sensitivity can be derived from modeling as well.

The method above can provide the optimized angles for one ray at one particular wavelength from the measurement of the one nominal structure. In reality it is necessary to integrate over all the rays, all the wavelengths, all the incident and azimuth angles, and then compromise between all key defects. Practically, it is much easier to optimize the polarization angles from a wafer with known defects.

Rudolph Technologies designed and built its first polarization imaging system on a macro inspection tool, the WaferView® 320. It has successfully demonstrated the sensitivity improvement for defocus and dose defects, with customer production wafers at multiple process nodes and at high throughput, while maintaining the same inspection capability for other defects.

Fig.3 shows some results for illustration purpose, using the scatterometry targets on a SEMATECH wafer (AMAG4L). The scatterometry structures have cells with different line feature size (30 nm to 500 nm), different pitch (1:1 to 9:1), and with positive and negative tunes. It is a montage of images captured at fixed cross-angle $P - A = 45^\circ$, and with different polarizer angles at 5° step in a circle. We can derive the optimized polarization configuration for the interested cells from these data.

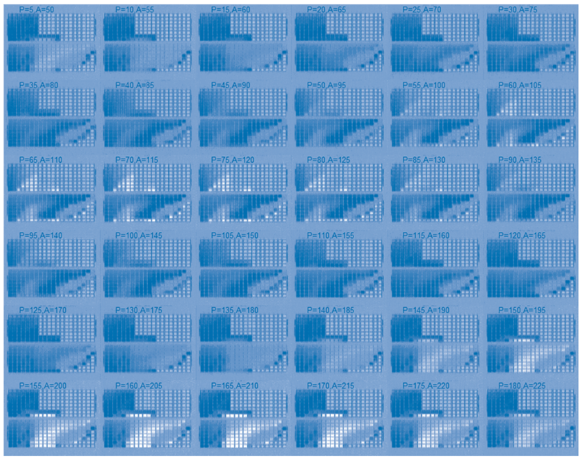

Figure 3 - Montage of images of scatterometry targets of a SEMATECH wafer, with fixed $P - A = 45^\circ$ *, and different polarizer angles at 5° steps in a circle.*

CONCLUSION

Rudolph introduced a new concept of polarization imaging for optical inspection, by optimizing the polarization state in the illumination to achieve the best performance for the key targets. A unique configuration was presented to improve the inspection sensitivity of defocus and dose defects, while maintaining the same sensitivity for other polarization independent defects. A demo tool was designed and built based on this concept, and has been successful in demonstrating the defocus sensitivity improvements with customer production wafers at multiple process nodes at high throughput.

Beyond defocus and dose defects inspection, the polarization imaging system has potential for many other applications as well.

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