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Improvement of on-cell metrology using spectral imaging with TCAD modeling

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ABSTRACT

On-cell metrology based on spectral imaging (SI) with TCAD modeling is developed for measuring advanced logic devices. Spectral imaging has been adopted because it can directly measure a cell-block of logic device, which could not be achieved with the conventional methodology. One of conventional methodology, optical critical dimension (OCD), assumes that the cell-block is infinitely periodic, so that relatively large metrological site is needed. However, SI has also disadvantages, it use only one spectrum type and narrow wavelength band. To overcome such limitations, we adopt TCAD modeling by providing realizable sets of spectrum and structure. TCAD model acts as a data augmentation of structural parameter and corresponding simulation spectrum. From sufficient learning data, their correlation was successfully obtained through machine learning. With the proposed method, we could obtain both wafer-to-wafer distribution and in-wafer distribution with a good tendency in logic devices.

1. Introduction

Non-destructive in-line metrologies of advanced logic devices are becoming important to prevent yield loss and evaluate electric characteristics. As the device scaling decreases and the development cycle shortens, its importance and necessity are increasing further [1–3]. Due to these demands, measurements at the cell level are required to obtain local characteristics which could not be achieved with optical conventional methodology. One of conventional methodology, optical critical dimension (OCD) [4,5] needs a large measurement area, assuming that the cell-block is infinitely periodic. Although OCD can obtain homogenized characteristics, local characteristics of the cell-level cannot be achieved [6].

To overcome such limitations, we propose the spectral imaging (SI) with TCAD modeling. SI system is on-cell metrology which can generate high resolution spatial images. From analyzing spatial images sets, it can obtain local characteristics of cell-block. However, since it measures only the reflectance of s-waves (*sR*) for the fast capturing, the number of data type can be a disadvantage. In this paper, this lack of spectrum type can be overcome through TCAD modeling by generating realizable structure and spectrum. With proposed method, the relationship between structural parameter and spectrum has been improved. As a result, the wafer distribution and its tendency of target values has been improved further. It showed superior consistency compared to the conventional method at blind validation.

2. Theoretical backgrounds

2.1. Optical system configuration

Schematic diagrams of OCD and SI system are depicted in Fig. 1. OCD system uses only one point source to wafer. The reflected light is split through the prism. The line charged-coupled device (CCD) can received broadband continuous wavelength. On the other hand, SI system incident discretized single wavelength but multi-points source to wafer. The monochromator takes only one wavelength from white light. The reflected light is captured as an image by the area CCD. Obtained images are stored according to wavelength one by one. The stack of images becomes a spectral cube as shown in Fig. 2(a). When gathering information according to the wavelength of the spectral cube at an arbitrary

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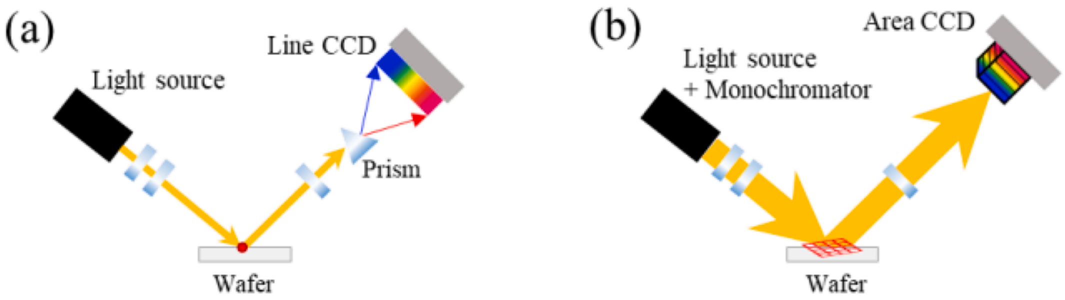

Fig. 1. Comparison of OCD system and SI system.

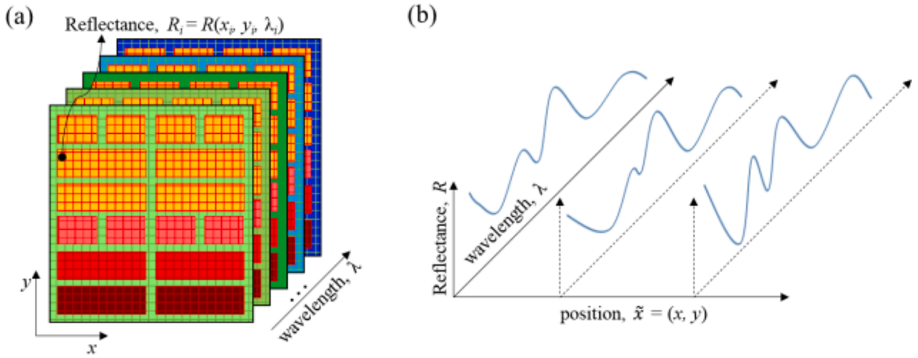

Fig. 2. (a) Obtained spectral images from SI system, (b) Spectra extracted in an arbitrary position.

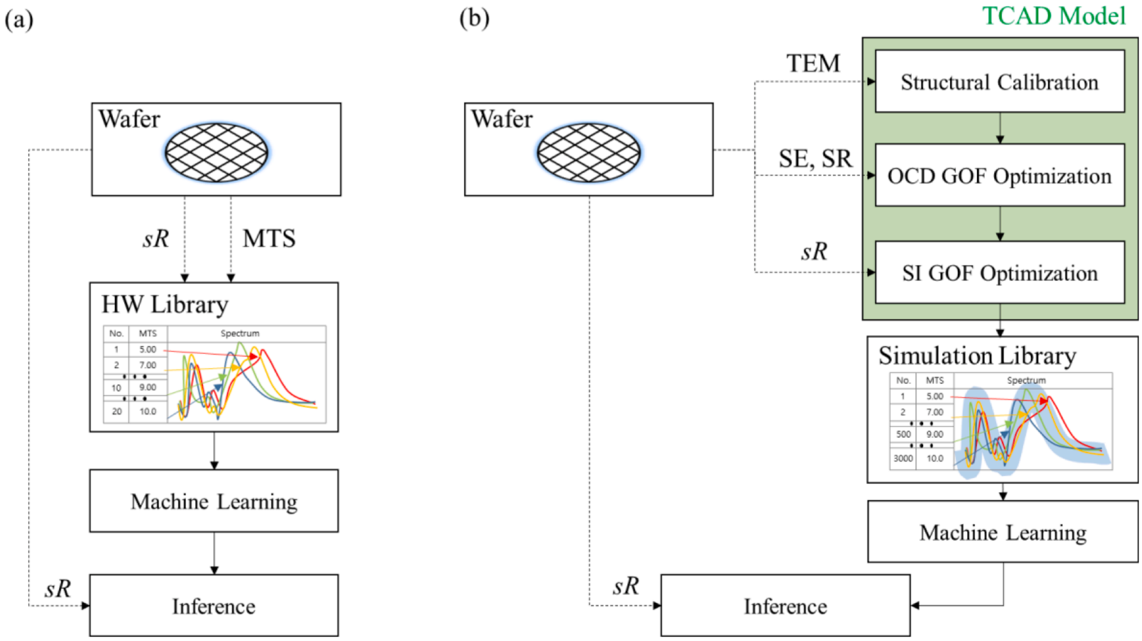

Fig. 3. Process flow of (a) conventional SI approach and (b) proposed method.

position, each spectrum for the wavelength can be obtained (See Fig. 2 (b)).

2.2. Methodology of SI system

SI system can acquire spectrum at multiple points with high resolution, but it has a relatively lack of data from its configuration. First, the wavelength band of SI has a relatively coarse, discretized, and narrow. Second, SI typically uses only one spectrum type such as *sR* to reduce the burden of data and increase capturing speed. Therefore, additional processing is necessary to compensate the lack of data.

In the conventional SI approach, *sR* signal and the module target spec (MTS) are learned directly (See Fig. 3(a)). MTS is a variable of interest, such as depth, thickness, and height. Because it does not require any modeling and physical analysis by direct learning, time consumption for data preprocessing is quite reduced. However, it is hard to collect sufficient data for learning owing to their economic cost and analyzing time. For example, actual MTS can be obtained from several analyzing method such as the transmission electron microscope (TEM) and scanning electron microscope (SEM) which are inherently expensive and

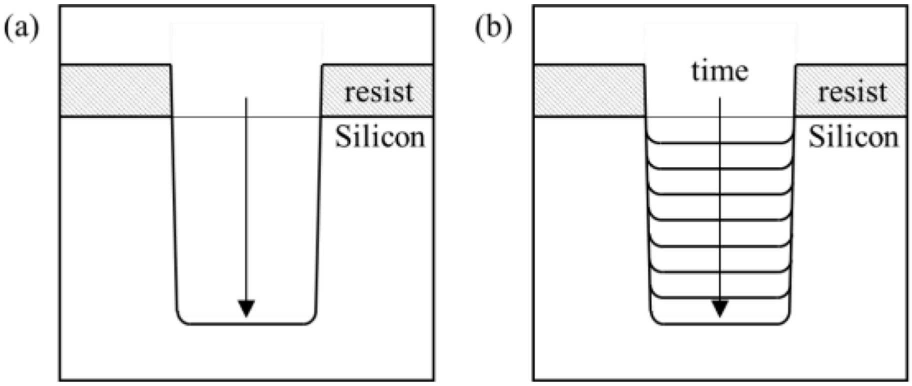

Fig. 4. Comparison between (a) emulation model and (b) simulation model.

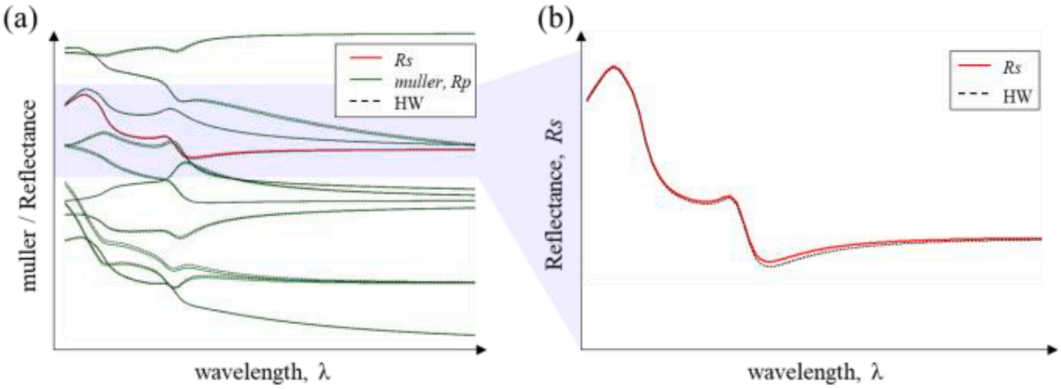

Fig. 5. GOF Optimization results of (a) OCD and (b) SI.

time-consuming.

As an existing method to solve such difficulties, the inferred MTS with OCD can be replaced with TEM and SEM. Engineers assume that the periodic structure exists in other places and it is sufficient large enough to apply OCD. However, the inferred MTS with OCD is difficult to represent the locality of cell-block. Because the resolution of OCD is larger than the period of logic devices. Therefore, MTS obtained through OCD has a slight difference compared to the actual one. Also, OCD uses modeling, additional preprocessing and setup time are required.

In this paper, TCAD model is adopted to replace the actual metrologies. TCAD model works as a data augmentation by perturbing process parameters and generating simulation data freely. As shown in Fig. 3(b), it is used in structural calibration and two-step GOF optimization. In structural calibration, the simulated structure is regenerated suitable for TEM. Engineers calibrate MTS with the desired values and manipulate curvature by perturbing process variables such as deposition thickness, etch time, and mask length. Depending on the modeling technique, TCAD models can be divided into emulation models and simulation models. Fig. 4 shows the comparison between them. Emulation models are mathematical models which can be directly obtained with simple calculation. On the other hand, simulation models are time-transient physical models that are possible to implement incoming factors or loading effects. In this paper, simulation models are adopted to represent complex process and shapes of the logic devices.

Simulation spectrum can be calculated with the rigorous coupled-wave analysis (RCWA) from the generated structures. The good of fitness (GOF) is defined to compare similarity between simulation and actual spectrum.

$$\mathrm{GOF}\left(\vec{\psi}_1,\vec{\psi}_2\right)=1-\frac{1}{L}\frac{1}{N_\lambda}\sum_{i=0}^{N_\lambda-1}\left|\vec{\psi}_1(\lambda_i)-\vec{\psi}_2(\lambda_i)\right| \tag{1}$$

where, $\vec{\psi}_1$ is the simulation spectrum and $\vec{\psi}_2$ is the actual spectrum. L is the normalization value, 2 for muller component and 1 for reflectance. λ_i is the i-th wavelength and N_λ is the number of binned wavelength.

For OCD GOF optimization, both spectroscopic ellipsometry (SE) and spectroscopic reflectometry (SR) are fitted at the same time. SE is the ratio of reflected p and s waves from oblique incident wave, for example muller components. SR can obtain the reflectance of s-waves (*sR*) and p-waves (*pR*) from normal incident wave. As shown in Fig. 5(a), both muller components and reflectance are fitted together in the broadband region.

After OCD signal is fitted, the SI GOF optimization focuses only *sR* signal in narrow wavelength band as shown in Fig. 5(b). By first fitting the various spectrum type in OCD signal, a range of feasible structures can be filtered.

Because TCAD models are free to construct, simulation libraries, which are pairs of spectrum and MTS, can be generated on demand. Fully connected neural networks (FCNNs) is adopted for machine learning. The input is the simulation spectrum and the output is inferred MTS. After learning is done, *sR* signals from the wafer can be inferred through the learning model as shown in Fig. 3(b).

3. Results and analysis

The proposed method is validated with the R2 test in setup and blind test. Also, its wafer distribution is checked whether the MTS scatter plot for wafer radius is distinguished from other wafers and has a similar shape between them.

In this paper, a specific step of a logic product was selected as a benchmark problem. The simulated structure of the cross section was fitted compared with the actual TEM. The optimized GOF of OCD and SI satisfies 0.98 or more respectively. Through machine learning process,

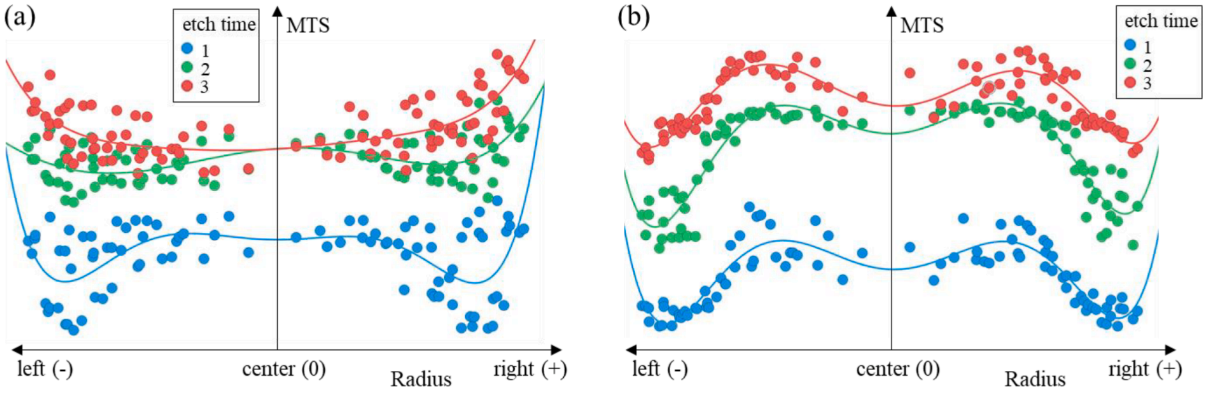

Fig. 6. Wafer distribution according to radius of (a) conventional SI and (b) proposed m.

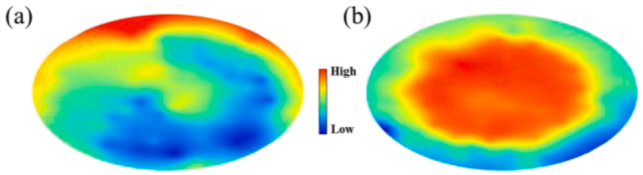

Fig. 7. Wafer map of (a) conventional SI and (b) proposed method at etch time equals 2.

the acceptable accuracy has been obtained at setup status, $R^2 = 0.90$.

Fig. 6 is the wafer distribution results according to the etch time comparing the conventional SI and the proposed method. In Fig. 6(b), the wafer-to-wafer distribution which is MTS change between other wafers is clearly distinguished with the proposed method. As the etch time increases, MTS becomes smaller. In addition, the in-wafer distribution, which is the intra-wafer MTS change, has a small deviation and configure a specific shape. It follows the characteristic tendency of low–high–low according to the radius change of center-middle-edge. The left and right MTS change must be mirrored, and the trend should be similar across different wafers. The results of the proposed method follow the conditions well. On the other hand, in the case of conventional SI, the wafer-to-wafer distribution becomes worse. Because etch time 1 and 2 are not distinguished as shown in Fig. 6(a). Also, the in-wafer distribution is not similar between them.

Fig. 7 shows the two dimensional wafer map of the conventional SI and the proposed method. Their values were inferred from median etch time in Fig. 6. When the conventional SI is used in Fig. 7(a), it is hard to figure out in-wafer distribution toward radius. On the other hand, the proposed method in Fig. 7(b) clearly shows the in-wafer distribution. There is a characteristic tendency of decreasing MTS towards the edge in all directions.

For verification, an additional blind test was performed as shown in Fig. 8. The experiment was performed about a month later after the setup. As a result, the conventional SI showed an inverse correlation with low R2 in Fig. 8(a), whereas the proposed method showed robust reliability with R2 of 0.9638 as shown in Fig. 8(b). It can be confirmed that the proposed method has a relative consistency advantage over time.

4. Conclusion

In this paper, we newly propose a spectrally resolved imaging system with TCAD modeling. From structural and optical calibration, TCAD model allows the generation of simulation libraries that resemble real data. Sufficient data for machine learning successfully replaces real world inspections such as TEM or SEM. The proposed method can reduce the number of validation wafers because the measuring costs and time are significantly reduced by replacing the actual inspection.

As a validation result, the R2 value was 0.90 in the setup test and 0.96 in the blind test. These values were higher than those of the existing method, and showed robustness even after one month. Also, the proposed method show better wafer distribution such as wafer-to-wafer and in-wafer distribution. It could not be achieved with the conventional method. From improved consistency and locality, the proposed method is expected to grasp early structural defects and contribute to yield improvement.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

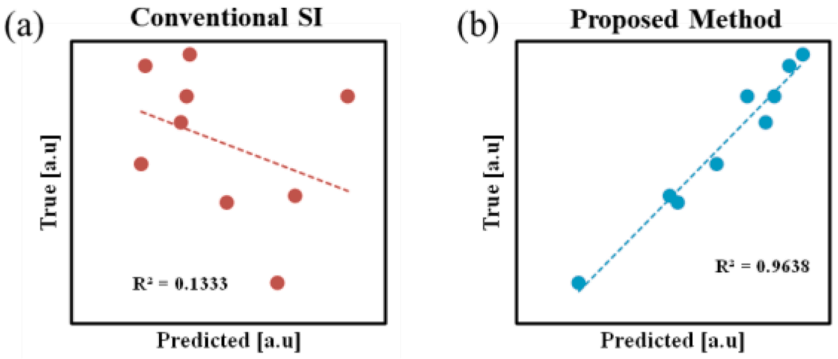

Fig. 8. Blind accuracy and of (a) conventional SI and (b) proposed method.

Data availability

The data that has been used is confidential.

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