Solid-State Electronics 200 (2023) 108574

Contents lists available at ScienceDirect

Solid State Electronics

journal homepage: www.elsevier.com/locate/sse

Sensitivity enhancement in OCD metrology by optimizing azimuth angle based on the RCWA simulation

Hyunsuk Choi [a,*], Kwangseok Lee [a], Jiseong Doh [a], Jaehoon Jeong [a], Taeshin Kwag [b], Minseok Kim [b], Yeonjeong Kim [b], Jongchul Kim [b], Hyung Keun Yoo [b], Dae Sin Kim [a]

[a] Computational Science and Engineering Team, Gyeonggi-do 18448, Republic of Korea
[b] Foundry Metrology & Inspection Technology Team, Samsung Electronics Co., Ltd., Gyeonggi-do 18448, Republic of Korea

ARTICLE INFO

The review of this paper was arranged by "Francisco Gamiz"

Keywords:
FinFET
MBCFET
Rigorous coupled wave analysis
Simulation
Optical critical dimension
Optical sensitivity

ABSTRACT

Monitoring process using optical critical dimension (OCD) metrology has been performed with a pre-fixed and unoptimized azimuth angle for all modules. Azimuth angle has a great influence on the optical sensitivity and can be easily tuned by changing the wafer rotation. In this study, we suggest the optimal azimuth angle for both FinFET and MOSFET device based on the rigorous coupled wave analysis (RCWA). For FinFET device, the optical sensitivity at the optimal angle was improved around 30% for two modules compared to that of pre-fixed angle. For MBCFET, we demonstrated that the simulated sensitivity is consistent with experiment and confirmed 10% sensitivity enhancement at 25 degree in experiment.

1. Introduction

For decades, Moore's law, the density of integrated circuit (IC) doubles every-two years, has been well applied [1]. With down-sized gate length, the modern semiconductor structure becomes more complicated and 3-dimensional. Thus, monitoring critical dimensions (CDs) of nanostructure in the fabrication process becomes more important [2–3]. Optical critical dimension (OCD) metrology, based on the scatterometry, is one of the powerful technique to investigate such complex structures [4–5]. The multi-parameter, fast and non-destructive characters of OCD make it a proper tool to investigate stacked nano-structures, such as FinFET or MBCFET device [6], which are invisible to top-down imaging methods.

Monitoring fabrication process using OCD has been performed for all modules with a pre-fixed incident and azimuth angle, typically 65 and 45 degree, respectively. Since, at the azimuth angle of 0 and 90 degree, the structure of device becomes symmetric, off-diagonal terms of Mueller component becomes zero. Thus, in most cases, 45 degree is set as the default angle. In the OCD measurement, it is hard to modify incident angle because resetting the measuring equipment can affect established condition. On the other hand, the azimuth angle can be easily tuned by changing the wafer rotation. In this study, we suggest optimized azimuth angle for 2 front-end modules of FinFET device to achieve higher sensitivity based on the rigorous coupled wave analysis (RCWA) simulation. To verify our simulation, we performed OCD measurement for the source and drain (SD) module of MBCFET device. In the experiment, 3 wafers with different etch condition were measured at the azimuth angle from 0 to 90 degree. Finally, the result is compared with the RCWA simulation.

2. Experiment

2.1. Sensitivity

In this study, sensitivity is defined as the difference in spectrum when a structure parameter is changed from its possible minimum to maximum value, as shown in Eq. (1). Here, $\psi_{\min}$ and $\psi_{\max}$ represents the Mueller spectrum of minimum and maximum CD, respectively. i denotes the upper-triangle terms of Mueller Matrix, except for the element in the 1st row and 1st column. N is the number of Mueller components and λ is the normalization factor, 2 for Mueller elements. The components are averaged for the wavelength, x.

---

[*] Corresponding author.
E-mail address: hs9207.choi@samsung.com (H. Choi).

https://doi.org/10.1016/j.sse.2022.108574

$$S = \frac{1}{N}\sum\nolimits_{i}^{N}\frac{1}{\lambda|x|}\int dx\left|\psi^{i}_{max}(\vec{x}) - \psi^{i}_{min}(\vec{x})\right| \tag{1}$$

2.2. Simulation details

Fig. 1 shows the schematic view of the FinFET structure, which was created by using Technology Computer-Aided Design (TCAD) modeling tools, developed in Samsung Electronics. Mueller spectrum of the structure was obtained by the RCWA simulation. The Fin width along y-axis (indicated by blue arrows in Fig. 1) is a few nanometers long and its height along z-axis is order of several tens of nanometers. The Gate length along x-axis (indicated by green arrows in Fig. 1) is a few nanometers long. The source-drain spacing and gate width are several tens of nanometers long. As shown in the figure, azimuth angle is defined as the angle between y-axis (normal vector of FinFET front surface) and the incident plane. In the simulation, azimuth angle is changed from 0 to 90 degree with the step size of 5 degree. The incident angle is fixed as 65 degree during simulation.

The simulation was performed for 2 front-end modules, Fin and Gate, of FinFET device. Fin or Gate module represents the step after the fabrication of Fin or Gate structure, respectively. For each module, Fin width and Gate length was set to be the critical structure parameter, respectively. Other structure parameters such as Fin height and Gate width, are fixed during simulation. For each azimuth angle from 0 to 90 degree, the critical structure parameter is set to be its minimum and maximum value and their Mueller spectra are obtained by RCWA simulation. Then, the sensitivity is calculated for each step, and the optimal azimuth angle is determined as the point where sensitivity shows its maximum.

2.3. Experimental details

The experiment was performed for source and drain (SD) step of MBCFET device. The OCD metrology was performed using Atlas 3 system (Onto Innovation) with sub-angstrom wavelength precision. The OCD system was pre-calibrated by the module target spec (MTS) of sample wafers measured by transmission electron microscope (TEM). In the measurement, azimuth angle was changed from 0 to 90 degree with the step size of 5 degree. The incident angle was fixed as 65 degree.

In the experiment, 3 wafers in the same lot that shares same fabrication process but with the different SD etch condition were prepared. Wafer #1 is the control group with the reference etch condition and other wafers, #2 and #3, are the experimental group with different etch times. In the experiment, SD profile was determined by several independent etch steps. Among them, we controlled the time of plasma etch and wet etch. Plasma etch is the anisotropic etch which shapes the vertical depth of SD profile. On the other hand, wet etch is the isotropic etch which determines the bowl shape. The detailed experiment condition is shown in Table 1. Here, Etch time 1 and 2 corresponds to the plasma and wet etch, respectively. As shown in the table, wafer #2 and #3 has 5 (s) shorter Etch time 2 than the reference. Moreover, wafer #3 has 2 (s) shorter Etch time 1, which makes shallower SD etch depth compared to the reference condition. Thus, wafer #1 and #3 shows the biggest difference in the nanosheet structure among 3 wafers. Then, their Mueller spectra were obtained for the wavelength range from 200 to 1000 nm.

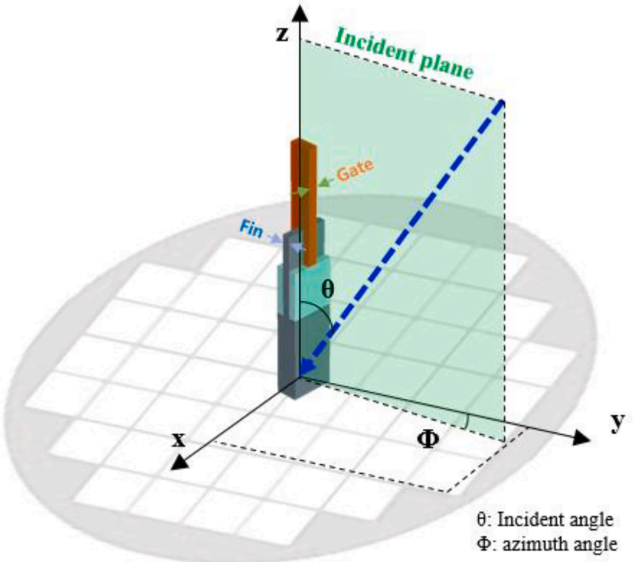

Fig. 1. Schematic view of FinFET TCAD model used for the RCWA simulation.

In the simulation, TCAD models of two wafers were constructed using plasma and wet etch simulation models. The simulation parameters such as etch rate, degree of anisotropy and etch time were calibrated from the TEM data. Then, the SD structure of the wafers were established by adjusting the simulation etch times while other structure parameters were fixed. Finally, the Mueller spectra of two wafer models, #1 and #3, were obtained by RCWA simulations for the azimuth angle from 0 to 90 degree. The simulation results were compared with the OCD measurement.

3. Results and analysis

3.1. FinFET

Fig. 2 shows typical Mueller spectra obtained by RCWA simulation at the front-end module of FinFET fabrication process. In the simulation, Fin width is changed in a few nanometer range and other structure parameters are fixed. For each Mueller component, it shows the spectrum of azimuth angle from 0 (purple) to 90 (red) degree. Based on Eq. (1), sensitivity is calculated for each azimuth angle. The results are shown in Fig. 3, where blue dots indicate the normalized sensitivity of Fin module and red dots indicate that of Gate module.

In the figure, sensitivity increases with increasing azimuth angle and decreases for the angle larger than 80 degree. At 0 and 90 degree, the structural symmetry recovers from the viewpoint of light. The symmetry makes off-diagonal terms of Mueller spectrum flat, as shown in Fig. 2 (purple and red line). The zero Mueller terms make the sensitivity low as described by the Eq. (1). Thus, the sensitivity increases from 0 and decreases over 80 degree. At the pre-fixed 45 degree, the raw value of sensitivity is 0.071, which is 0.024 smaller than the maximum value of 0.095. Typically, around 0.01 difference in sensitivity is an observable change in the OCD measurement. Thus, 80 degree will be the optimal azimuth angle for distinguishing Fin width. Same analysis applied for the Gate module of FinFET, where the Gate length was the critical parameter to be controlled. The sensitivity for Gate length has its maximum value of 0.225 at 20 degree, which is the opposite result of Fin module. This result is consistent with our common sense that Fin width and Gate length can be easily seen at the side view and front view of FinFET structure, respectively.

The detailed results are shown in Table 2. In the table, sensitivity indicates the raw value before normalization and the enhancement was calculated based on the value at 45 degree. Comparing to the pre-fixed azimuth angle, sensitivity at the optimal point is enhanced 33.8 % and 28.6 % for Fin and Gate module, respectively.

Table 1
SD etch condition of wafers, #1, 2 and 3.

Wafer #	Etch time 1	Etch time 2
1	Ref	Ref
2	Ref	Ref – 5 (s)
3	Ref – 2 (s)	Ref – 5 (s)

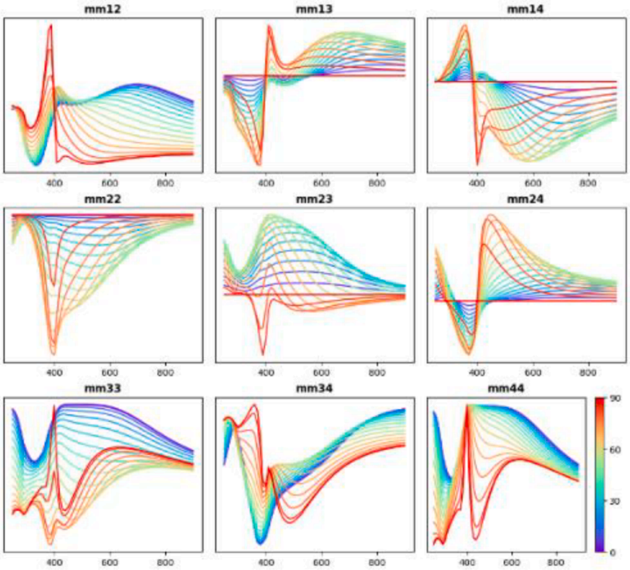

Fig. 2. Typical Mueller Matrix elements of FinFET device obtained by RCWA simulation.

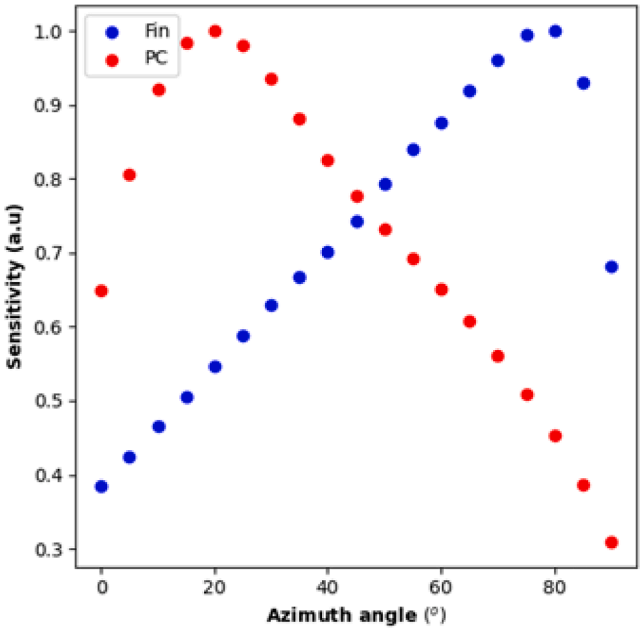

Fig. 3. The normalized sensitivity of Fin (blue dots) and Gate (red dots) module, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
The raw sensitivity and its enhancement at the optimal azimuth angle for two FinFET front-end modules.

Step	Azimuth angle	Sensitivity (a.u.)		Enhance
		As-Is	To-Be	
Fin	80 degrees	0.071	0.095	33.80 (%)
Gate	20 degrees	0.175	0.225	28.57 (%)

3.2. MBCFEt

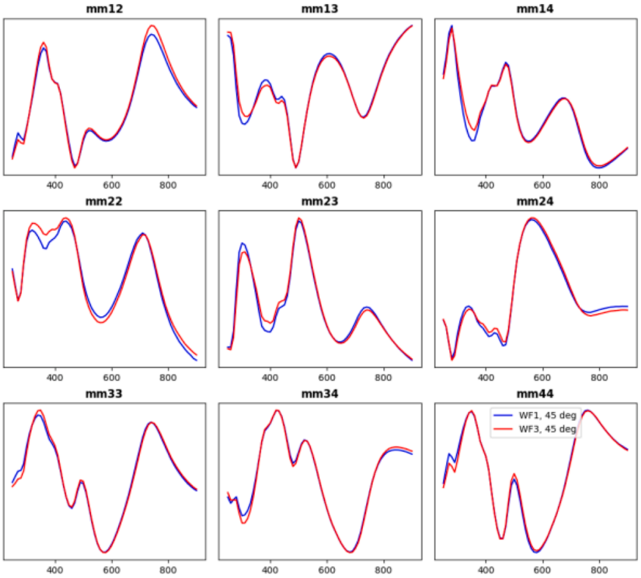

Fig. 4. Typical Mueller spectra of SD module of GAA device.

Fig. 4 shows typical Mueller spectra obtained by OCD measurement for the SD module of MBCFET device. Here, blue line represents the spectrum of wafer #1 with the reference etch condition, and the red line represents wafer #3, which has the shorter etch time, at the azimuth angle of 45 degree. The spectra were obtained for the azimuth angles from 0 to 90 degree. The difference in Mueller spectra between two wafers, #1 and #3, was calculated based on Eq. (1), for each azimuth angle. RCWA simulation was also performed for the same etch condition.

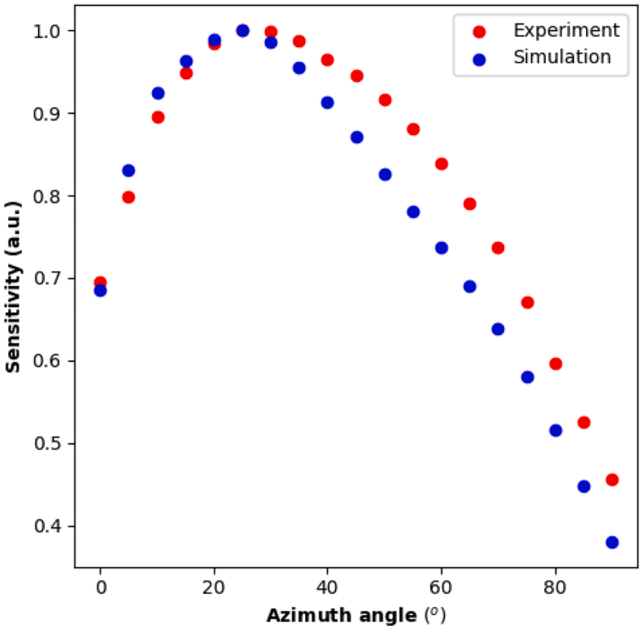

Fig. 5. The normalized sensitivity plot for the experiment (red dots) and simulation (blue dots) of GAA device, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The calculated sensitivities are shown in Fig. 5, where red dots indicate normalized sensitivity of OCD measurement and blue dots are that of simulation result. Here, the maximum value of each result was normalized to be 1 for the experiment and simulation, respectively. As shown in the figure, sensitivity increases with decreasing azimuth angle and has its maximum value at 25 degree for both experiment and simulation result. For the azimuth angle smaller than 80 degree, sensitivity decreases as the off-diagonal terms of Mueller spectra become close to zero. The measured position of optimal azimuth angle and the tendency is consistent with the RCWA simulation.

At the pre-fixed 45 degree, the value of normalized sensitivity is 0.911 and 0.872 for measurement and simulation, respectively. Compared to the sensitivity at 45 degree, sensitivity is enhanced 9.82 % and 14.73 % for each case at the optimal azimuth angle of 25 degree. The detailed results are shown in Table 3. In the table, sensitivity shows the raw value before normalization and the enhancement was calculated based on the value at 45 degree.

4. Conclusion

In this study, we suggested the optimal azimuth angle for Fin and Gate module of FinFET device based on the RCWA simulation. The optimal angle was found to be 80 and 20 degree for Fin and Gate step, respectively. At the optimal angle, sensitivity was enhanced 33.8 % and 28.57 % for each module, compared to the pre-fixed angle. We applied our analysis for the SD module of MBCFET device and the results were consistent with the OCD measurement data. The optimal angle was found to be 25 degree for both cases. At the optimal angle, sensitivity was enhanced 9.82 % and 14.73 % for experiment and simulation, respectively, compared to the pre-fixed angle. Through the proposed optimization method, we improved the optical sensitivity and expect to catch the structural defects more easily.

Table 3
Sensitivity at prefixed and optimal azimuth angle for a GAA SD module.

	Optimal angle	Sensitivity (a.u.)		Enhance
		As-Is	To-Be	
Exp.	25	0.0112	0.0123	9.82 (%)
Sim.	25	0.0224	0.0257	14.73 (%)

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.

Data availability

The data that has been used is confidential.

References

[1] Mack CA. Fifty years of Moore's law. IEEE Trans. Semicond. Manuf. 2011;24(2): 202–7.
[2] Orji NG, et al. Metrology for the next generation of semiconductor devices. Nat. Electron. 2018;1:532–47.
[3] Foucher, J., Ernst, T., Pargon, E. and Martin, M., "Critical dimension metrology: perspectives and future trends," SPIE Newsroom (2008).
[4] Garcia-Caurel E, et al. Application of spectroscopic ellipsometry and Mueller ellipsometry to optical characterization. Appl. Spectrosc. 2013;67(1):1–21.
[5] Hoobler, Ray J., and Ebru Apak. "Optical critical dimension (OCD) measurments for profile monitoring and control: applications for mask inspection and fabrication." *23rd Annual BACUS Symposium on Photomask Technology*. Vol. 5256. SPIE, 2003.
[6] Bae G, et al. 3nm GAA technology featuring multi-bridge-channel FET for low power and high performance applications. 2018 IEEE International Electron Devices Meeting (IEDM). 2018.