Accurate and Reliable Optical CD of MuGFET down to 10nm

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ABSTRACT

As device critical dimensions (CD) decrease, they approach the limits of standard metrology techniques and measuring features smaller than 20 nm represents a serious challenge. Within the framework of the 32 nm program at IMEC, a reliable and accurate approach to small feature metrology is required. We describe here a methodology aimed at measuring features down to 10nm by means of scatterometry. The results are compared to calibrated CDSEM measurements [1]. The active fins of a Multi Gate Field Effect Transistors (MuGFET) was measured across wafer and across batch. Scribe to cell correlation, wafer fingerprint, 3D profile, oxide thickness were also investigated. In particular, 3D profile information was compared to TEM. Our approach produced very consistent results for all measurement techniques (scatterometry, CDSEM and TEM) and it is now fully integrated in the IMEC production line to monitor the MuGFET platform.

Key words: scatterometry, ellipsometer, metrology, MugGFET, CDSEM.

1. INTRODUCTION

In recent years the critical dimension of printed devices is reaching the limits of standard metrology techniques. In the semiconductor industry, the measurement of features smaller than 20 nm is a challenge. In the frame of the 32 nm program at IMEC, the measurement of these critical dimensions requires a reliable technique.

The fins of a Multi Gate Field Effect Transistor (MuGFET) device can be as small as 10nm. This means that besides the classical precision requirement, the metrology tools have to guarantee accuracy. A 5nm accuracy error would correspond to a 30% change in critical dimension (CD) when dealing with a 15nm feature, which is not acceptable. In the current development phase, the accuracy requirement is often satisfied by expensive characterization techniques, such as transmission electron microscopy (TEM) analysis. This approach is obviously not sustainable in a production environment.

This paper presents the results of measurements of MuGFET structures from 60 nm down to 7 nm. They are made of isolated (pitch 320 nm) silicon lines on an oxide layer. We describe the methodology which uses two techniques (CDSEM and scatterometry) for comparison. In addition to CD, scatterometry technique provides additional parameters of profile and thicknesses. The fingerprints of the materials thickness are very consistent from wafer to wafer. The profile is compared to TEM pictures of the same scatterometry targets. The stability and reliability of the measurement of the side wall angle of the fins is discussed.

2. DESCRIPTION OF THE ACTIVE FIN

All exposures were performed on an ASML PAS5500/1100 step-and-scan system, interfaced with a TEL Clean Track ACT8. For the baseline technology integration work (front-end of line, FEOL), a 193nm resist from JSR, AR237J at 230nm Film Thickness (FT), is used on Brewer Science ARC29a organic Bottom Anti-Reflective Coating (BARC), FT = 77nm. The stack for MuGFET patterning (active layer) is 65nm silicon on 150nm buried oxide (= SOI stack, silicon-on-insulator). A 60nm TEOS oxide Hard-Mask (HM) is used during the patterning process for two reasons; providing etch resistance for the silicon etch and enabling CD (HM) trimming. A binary mask (BIM) is used to print CD of 100 nm in a pitch of 350nm. This target is chosen to have acceptable process latitudes (CD control) in litho. Two exposure conditions are studied in more detail: 0.63NA conventional illumination with 0.89σ and 0.75NA annular illumination with 0.89

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outer σ and 0.65 inner σ. After trim etch the CD target is 20 to 40 nm. An example of a fin in a MuGFET (after poly etch) device is shown in figure 1.

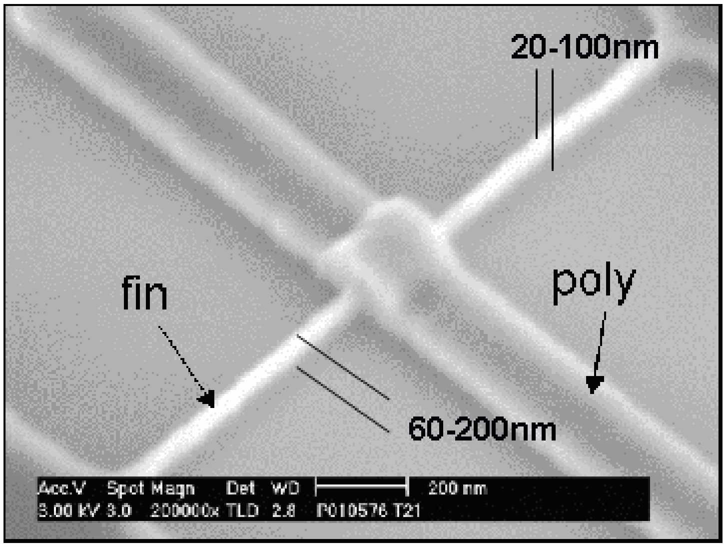


Fig. 1. A Fin in a MuGFET device.

The scatterometry measurements are done on a KLA-Tencor Spectra FX100 which uses a polarized ellipsometer. The scatterometry target is 50x50 μm^2. Top-down CDSEM inspection is done on a KLA-Tencor eCD2. In all IMEC designs, next to the standard scatterometry target, 2 additional targets are added with a bias in the CD but keeping the pitch constant (+/-20 nm is the standard bias used). In total, seven scatterometry targets are available in each die. They are all measured in every die with both tools. The description of these seven targets is given in table 1.(3 in the center with 0, +20 and -20 nm bias, 4 in each corner with no bias)

Table. 1. Scatterometry targets description

Scatterometry target design	Position
No bias (pitch 320 nm)	Center + each corner
+ 20 nm bias (pitch 320 nm)	Center
- 20 nm bias (pitch 320 nm)	Center

3. CDSEM CALIBRATION

We developed 4 different CD standards (70, 45, 25 and 13nm). The standards were obtained by depositing alternating layers of silicon and silicon oxide. The wafer is then diced and rotated, and the oxide is etched. The uniformity of the CD is mainly dictated by the deposition uniformity, which can be carefully controlled. This permits to obtain standards having very low roughness. By using this procedure, it is possible to create features having an extremely uniform and well-controlled CD over various millimeters.

The sample is then certified NIST traceable by using TEM analysis. The CD of the line is measured by comparing it to the lattice constant of the crystalline silicon of the wafer.

By using these accuracy standards, it was possible to optimize the measurement algorithm for accuracy. This step was obtained by mapping the total measurement uncertainty (TMU), as well as accuracy slope and intercept, as a function of the algorithm parameters. This procedure permitted a single set of parameters to be identified that guarantee the best

CDSEM accuracy in the range of interest. The measurement precision after accuracy calibration was observed to be less than 1nm [2].

4. SCATTEROMETRY MODEL DESCRIPTION

4.1 Libraries description

The libraries were generated using version 4.0 of the KLA-Tencor Spectra Creator software. Based on X-section pictures obtained during development, the profile is modelled with a side wall angle (SWA) close to 90 degrees and a small fixed bowing. As described above, the active fins are on a field oxide. The oxide hard mask removal (wet etch) creates a recess which we fixed at 5 nm. To study the sensitivity of the profile determination, two libraries are generated: with a fixed angle (called constrained library) and with a floating angle (called free library). Figure 2 shows a schematic X-section of the model of the feature. It is composed of two so called trapezoids (amorphous silicon which is the main trapezoid + oxide recess which is the secondary trapezoid) and an underlayer. Oxide and Silicon film models are the standard ones used in IMEC. The film model of the amorphous silicon has been measured on the wafer after patterning. SWA is defined according to the complete stack (silicon+recess).

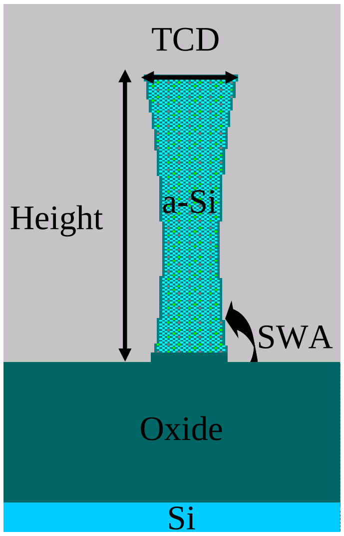


Fig. 2. Scematic profile of the scatterometry model.

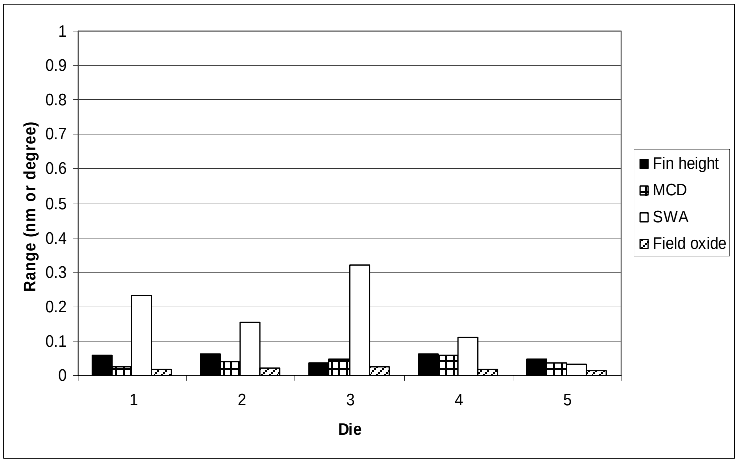
The parameters are described in table 2. Bowing and recess in the oxide are fixed (respectively -5 and 5 nm). The SWA limits described here are only valid for the free library. The SWA is fixed at 90 degrees for the constrained library.

Table. 2. Library parameters

	Minimum	Maximum	Step
Middle CD	4 nm	76 nm	2.25 nm
SWA	83 deg	101 deg	1.3 deg
Field oxide thickness	130 nm	170 nm	4 nm
Si thickness	56 nm	76 nm	2.5 nm

4.2 Repeatability results

Five dies are measured ten times dynamically (wafer is realigned each time but not unloaded). The fifty spectra are saved. The analysis of these same spectra is done with both libraries. The numbers reported in figure 3 are the range values of the ten measurements for every die.



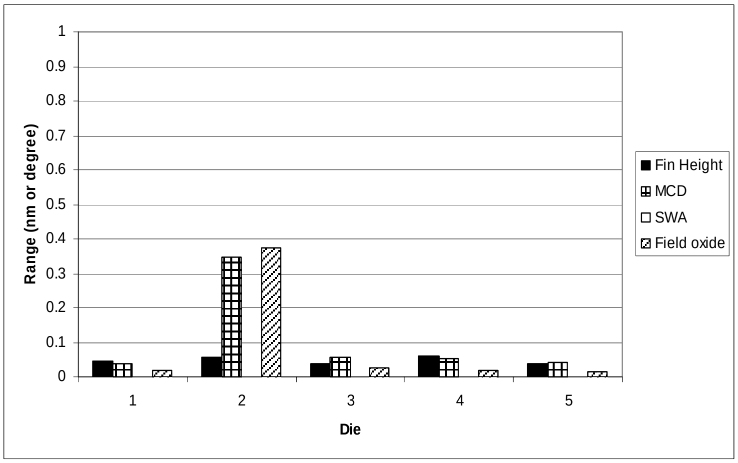


Fig. 3. Repeatability results for all parameters with two scatterometry libraries (fixed SWA on the top, floating SWA on the bottom) using the same spectra acquired on the central target without bias.

Fixing the SWA introduces some instability in the measurements (die 2 in the center of the wafer). Meanwhile a floating SWA does not show it, despite the fact the same spectra were used. Nevertheless, the repeatability numbers with a fixed SWA are below 0.4 nm for all parameters.

As already mentionned, two additional targets are available with a bias in the CD. These two additional targets are useful to see the response of the library to known variations. Repeatability results on biased fin (+/- 20 nm) with a fixed SWA shows comparable numbers. All parameter ranges are below 0.2 nm for large fins, meanwhile the ranges are below 0.5 nm for small Fins. However with a floating SWA the repeatability of SWA results is much worse, mainly for small fins but even in one case for large fins.

4.3 Discussion on profile determined by scatterometry

All the scatterometry targets without bias (five per die) over a full wafer are measured and the spectra saved. In addition to the two described libraries, a third library is generated without bowing (all the other parameters are the same). The CD and thicknesse results using these three libraries on the same saved spectra are shown in figure 4. The results (signature, average or 3 σ) are comparable and independant of the library used. This demonstrates the lack of sensitivity towards profile. The fins have three specific characteristics that can explain this. First, being the CD small, so we might have reached the ultimate limit of this measurement technique. Second, the features are very isolated (20 nm CD for 350 nm pitch), so the signal scattered is weak. Third, the features are rough (it can be half of the CD for the smallest lines of 10 nm), which adds noise to the scattered signal. One or a combination of these reasons can explain the lack of sensitivity observed. This needs more investigation and will not be addressed in this paper.

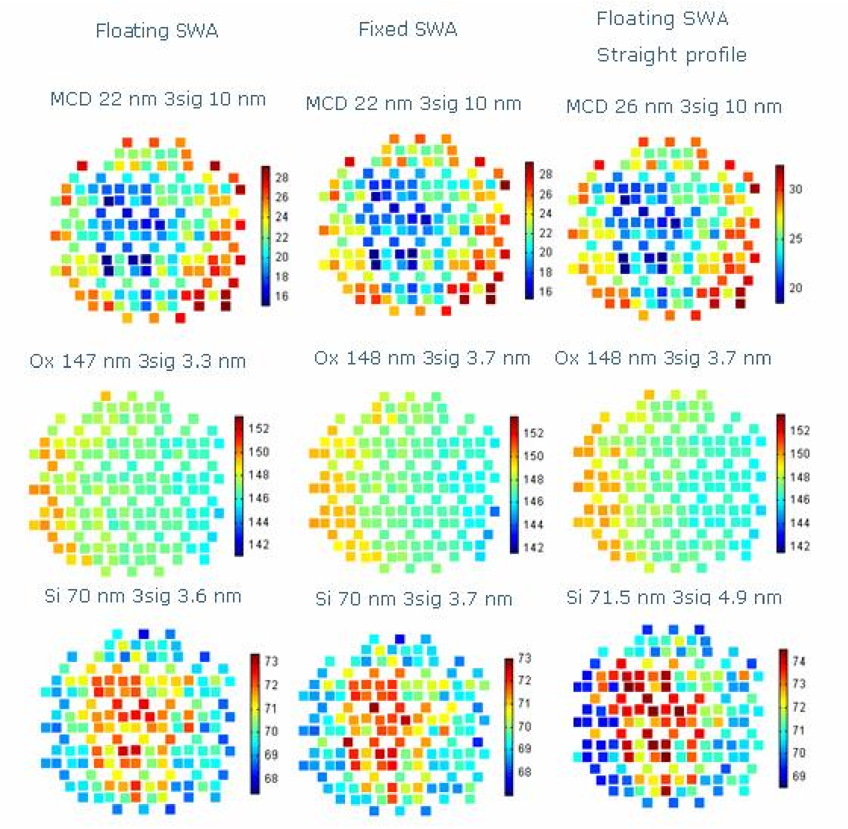


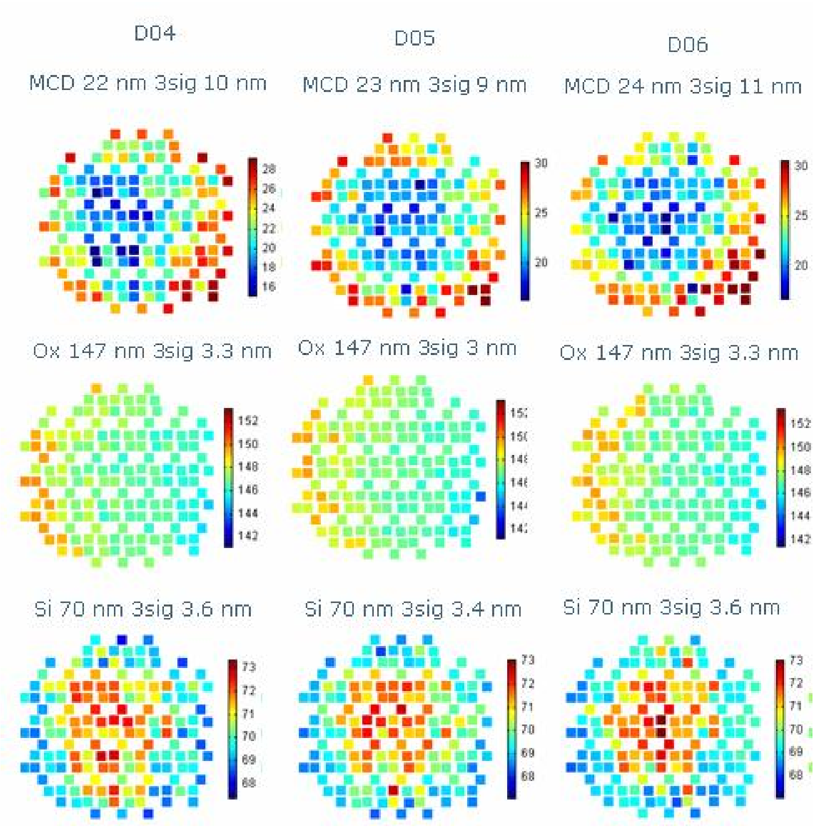
Fig. 4. Wafer signature of MCD (1st row), Field oxide thickness (2nd row) and amorphous silicon height (3rd row). The 1st column is using the “free library”, the 2nd column is using the “constrained library”, the 3rd column is using a library with a straight profile and floating SWA.

The SWA signature (not shown here) does not show any pattern. The ranges of values obtained is from 4.8 degrees for the straight profile to 7.6 degrees for the bowed profile. This lack of sensitivity is disappointing because any deviation of the profile of such structures has a strong impact on the performance of the device. Nevertheless, it is possible to detect the deviation but not its amplitude. As already published in one of our previous paper [3], some secondary parameter will deviate with the SWA. The most obvious one is the goodness of fit. This parameter shows a maximum when the profile is 90 degrees.

Based on these results (repeatability and fingerprints comparison), the library used in the following chapters will be the bowed profile with a fixed SWA of 90 degrees.

4.4 Wafer to wafer signature

In figure 5, the fingerprints of all parameters are compared between three wafers of the same lot (all wafers processed together). As already mentioned, the library with a fixed SWA was used for all the wafers. Five points per field were measured in all fields (scatterometry targets without bias). As can be seen, the mean values and the fingerprints are very stable wafer to wafer.



D04 MCD 22 nm 3sig 10 nm

D05 MCD 23 nm 3sig 9 nm

D06 MCD 24 nm 3sig 11 nm

Ox 147 nm 3sig 3.3 nm

Ox 147 nm 3sig 3 nm

Ox 147 nm 3sig 3.3 nm

Si 70 nm 3sig 3.6 nm

Si 70 nm 3sig 3.4 nm

Si 70 nm 3sig 3.6 nm

Fig. 5. Scatterometry results of the middle CD, Field oxide thickness and main trapezoid thickness (a-Si + 5 nm recess) of 3 wafers

4.5 Linearity of a programmed variation

In figure 6, the top CD of the three central targets with different biases show clearly the programmed bias in a consistent way through the wafer. Obviously, the CD values below 5 nm are measurement failures. CDSEM images of these scatterometry targets (TCD < 5 nm) show a lot of broken lines. Meanwhile all targets above that value appear correctly patterned.

Looking at the other parameters of the scatterometry model, the oxide thickness signature remains consistent independently of the target measured (as shown in the figure 8). The amorphous silicon height is consistent between the two targets without bias and +20 nm bias. But the -20 nm biased target gives larger variation over the wafer, even if the fingerprint is consistent with the two other targets. This height variation of the line can be linked with the reduced CD. The height is 70 nm when the TCD is higher than 10 nm, but can go down to 64 nm when the CD goes down to 6 nm.

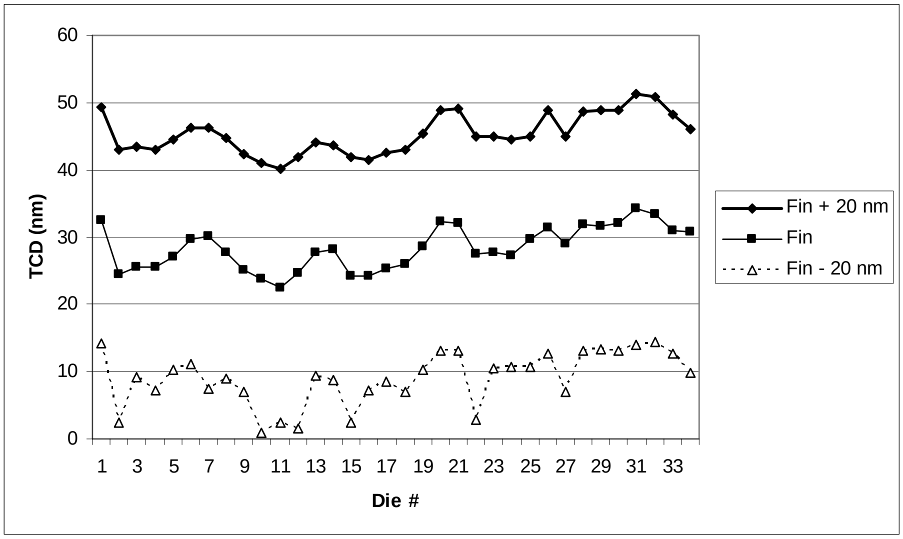


Fig. 6. Scatterometry results of the top CD of 3 targets (No Bias, Bias + 20 nm, Bias – 20 nm) through one wafer.

5. CDSEM-SCATTEROMETRY-TEM COMPARISON

5.1 CDSEM-Scatterometry correlation plot

The 7 scatterometry targets (5 without Bias, 1 with +20 nm, 1 with -20 nm) were measured in every die of a wafer with the CDSEM and the ellipsometer. In figure 7, the correlation between the top CD of the scatterometry model and the CD obtained with CDSEM is plotted. The correlation between the two techniques is 0.98 with a bias of 2 (small CDs) to 5 nm (large CDs).

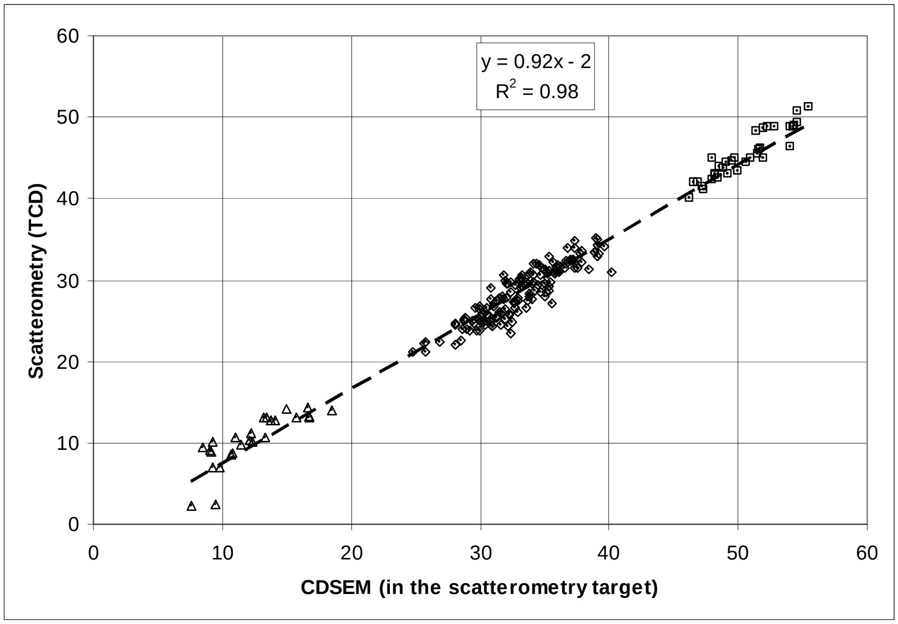


Fig. 7. Correlation plot of Top CD from scatterometry versus CDSEM results.

The main difference between the two measurement techniques lies in the amount of lines measured. The CDSEM measures a line in the center of the target, meanwhile the FX100 measures the average of all the lines in a spot of 30 um diameter. To evaluate the CD variation inside a scatterometry target (50x50 um), we measured using the CDSEM 49 points in the central scatterometry target without bias for 6 dies. The CD range inside a target is between 3 and 4 nm, and can be attributed to the impact of line edge roughness. This can explain a part of the differences observed between the two metrology techniques. Figure 8 shows the good agreement of Top CD signature between CDSEM and scatterometry.

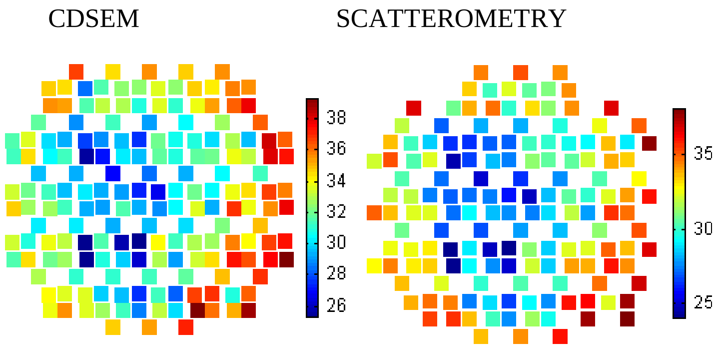


Fig. 8. Wafer signature of CD comparison between CDSEM (mean value 33 nm, 3 sigma 9 nm) on the left and scatterometry (top CD mean value 32 nm, 3 sigma 10 nm) on the right.

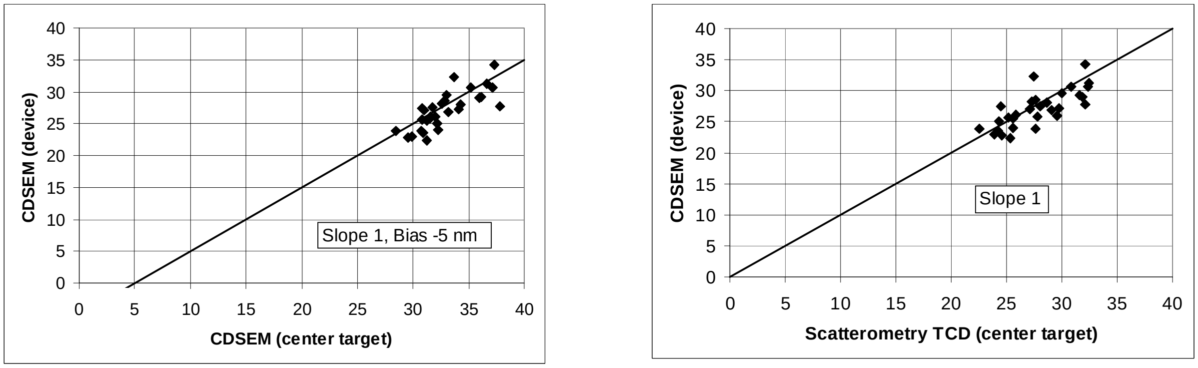


Fig. 9. Correlation plot of Top CD scatterometry and CDSEM measurements of the scatterometry target in the center of the field versus CDSEM measurements of the device in the field.

In figure 9, the correlation with real device measurement is presented. These measurements are done with the same CDSEM recipe defined in section 3. The structures used are in the center of the die, a few hundred micrometers away from the scatterometry targets. The bias of 5 nm mentioned in the first plot has to do with the scatterometry-CDSEM bias. Slope 1 line indicates the 1:1 correlation slope. Both techniques demonstrate their capability to monitor such processes

5.2 CD signature of the wafer compared to TEM

TEM pictures of the scatterometry targets were taken (in the center of the wafer and at the bottom right edge). It shows a clear bowing in the profile of the etched fins. The height of the amorphous silicon is measured by TEM around 63 nm, close to the 65 nm (70 nm total height - 5 nm recess) measured by scatterometry.

The CD wafer signature observed with CDSEM and scatterometry (figure 8) is confirmed by TEM. It shows a small CD value (24-26 nm with TEM; 25-28 nm with scatterometry) in the center of the wafer and a higher CD at the bottom right edge of the wafer (29-37 nm with TEM, 35-37 nm with scatterometry).

6. MONITORING RESULTS

In figure 10, the results of the monitoring of three lots measured with scatterometry and CDSEM are shown. Even though the wafer to wafer variation in a lot is not perfectly matched, the lot to lot variation is nicely tracked.

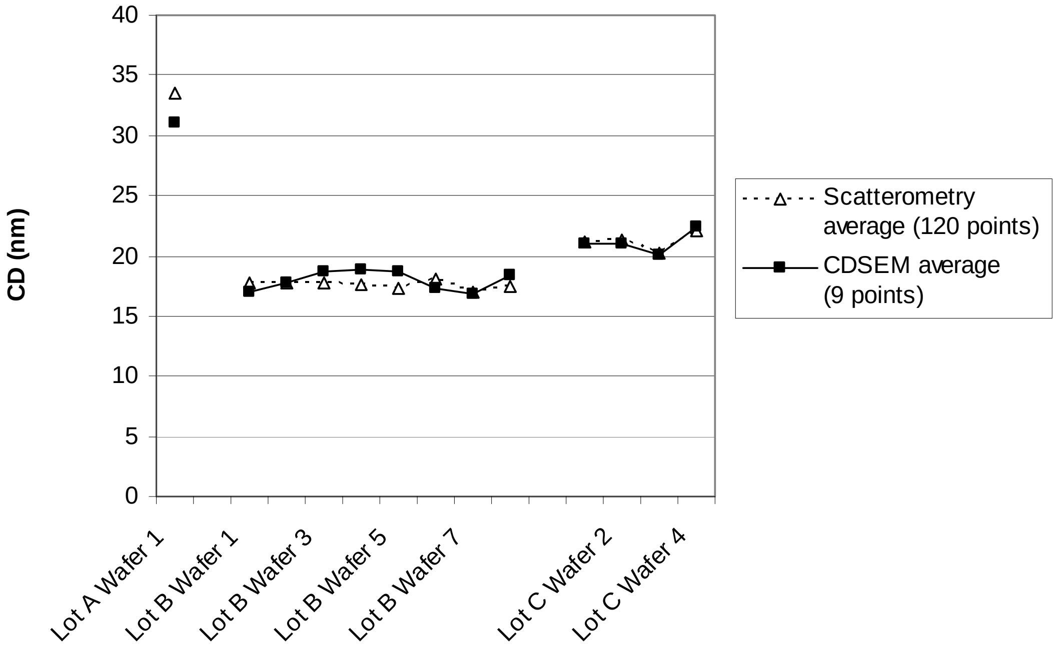


Fig. 10. Average values of CD for 13 wafers of three different lots. CDSEM and Scatterometry measuremenst are compared wafer per wafer.

7. CONCLUSION

A methodology to measure features down to 10 nm using scatterometry has been demonstrated. The comparison of scatterometry with two other techniques (CDSEM and TEM) showed consistent results (accuracy, CD signature, thickness of the fin).

The scribe to cell correlation is good. The field oxide thickness wafer signature does not show any correlation with other scatterometry parameters. The wafer CD fingerprint is stable wafer to wafer and lot to lot.

Due to a lack of sensitivity towards the profile information, only a fixed SWA at 90 degrees ensures the stability of the results. Nevertheless, the deviation from the fixed profile can be detected with the goodness of fit.

IMEC P-line is using the scatterometry recipe defined in this paper to monitor the MugFET platform.

8. REFERENCES

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9. AKNOWLEDGEMENTS

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