Characterization of the Poly Gate ACI Structure with Laser Based Angle Resolved Multiple Wavelength Scatterometry

Gary Jiang, Michael Kotelyanskii, Fei Shen

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ABSTRACT

Optical metrology techniques are essential for process control of gate formation process steps from lithography to the dielectric, spacers, gate and straining layer deposition in sub-90 nm technology nodes. Traditionally, optical metrology is based on the measurement of periodic lines or hole arrays using a spectroscopic ellipsometer or reflectometer, collecting data across a wide wavelength spectrum at a single angle of incidence. In this paper, we present results of measurements on periodic Poly-Si gate line arrays using laser based Focused Beam Scatterometry (FBS), illuminating at 3 discrete laser wavelengths while data is collected over an angle of incidence range from 45° to 65°. Accuracy, repeatability, and tool-to-tool matching results for the poly-Si gate line arrays are discussed. Comparison with the CD-SEM and cross-section TEM result for measurement/ modeling accuracy is also presented.

INTRODUCTION

With rapidly shrinking dimensions of the on chip gate width, fab process requires accurate control of the poly gate process. The tight metrology requirements for different process nodes have been outlined in 2006 ITRS[1]. For after etching (AEI) and after cleaning (ACI) poly gate, interested metrology parameters are poly thickness, critical dimension, and side wall angle. Comparing to direct characterization techniques such as scanning electron microscopy (SEM) or atomic force microscopy (AFM), scatterometer for optical critical dimension (OCD) measurement is faster and nondestructive, allowing users to incorporate them in real-time process control. TEM, SEM, and AFM are often used as reference metrology. OCD was measured widely with spectroscopic scatterometer which collects ellipsometry signal over a range of spectrum at a fixed incidence angle. Ellipsometry results were then compared against a pre-generated library by RCWA with a certain range of structure parameter variation, to obtain structure parameter values after library interpolation and lookup[2-4]. In this study, a laser based multi-angle scatterometry, Focused Beam Scatterometry, was used to characterize poly-Si periodic line grating arrays (ACI poly structure). FBS provides a simultaneous measurement of Delta and Psi, within a range of incidence angles from 45 to 65 degrees, at a discrete set of wavelength of 633 nm , 784 nm , and 923 nm. Simultaneous multi-angle measurement is achieved by focusing a collimated beam to a 15 μm spot onto the sample using projecting lens and collecting reflected light with the similar lens focused at the same spot. Figure 1 shows the Focus Beam Ellipsometry implementation.

RCWA-based algorithm was developed to calculate polarization and intensity of the scattered light from periodic gratings, based on the model of the sample cross-section, incident light wave vector and polarization state. Non-linear regression was used to fit measured data directly to optimize the model. Sensitivity analysis was also used to determine the optimal measurement and modeling configuration. Performance can be estimated by the sensitivity algorithm using the laser noise as input. Library-based lookup and interpolation are used for on-tool measurements, providing same throughput as flat film production runs.

RUDOLPH TECHNOLOGIES

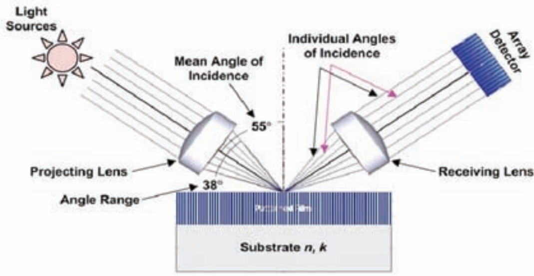

Figure 1 - *Focused Beam scatterometer: collimated beam from the light source is focused at the small spot on the sample by projecting lens, and reflected light is collected by the receiving lens. Array detector resolves the light scattered at different angles simultaneously from the sample across the beam cross-section.*

The ACI sample has periodic poly silicon lines on gate oxide structure with about 50 nm poly CD, 100 nm poly thickness, and 180 nm line pitch. Long term repeatability data was collected with 76 repeats over a 5 day period. TEM cross section was done after the FBS characterization to check the accuracy of structure profile generated from FBS measurement. Same measurement sites were also measured by CDSEM to compare the across wafer CD uniformity from FBS measurement. Two tools with same FBS configuration were used to collect tool-to-tool matching data.

RESULTS

Two models were used for the ACI structure. Figure 2(a) shows a double trapezoid model with top CD, bottom CD, mid CD at waist, waist relative height, and poly T. All the parameters were allowed to float during the non-linear regression to get the best accuracy for the structure. Footer height, side wall angle can be calculated from the above 5 parameters. This allows characterization of the footer height, and any under or over etch during poly etch process. Figure 2(b) shows a simplified structure based on the optimized structure with top CD, bottom CD, and poly T, for CD and height monitoring. Chi-square between measured and modeled ellipsometer parameters was used to indicate the convergence and fit of the model, as shown in Figure 3.

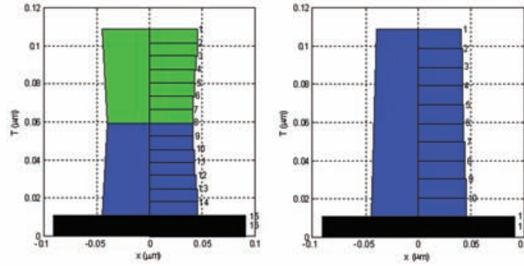

Figure 2 - *Structure models of ACI poly structure. (a) Double trapezoid model with top CD, bottom CD, mid CD at waist, waist relative height, and poly T. (b) Trapezoid model with top CD, bottom CD, and Poly T. The right half shows the sliced structure for RCWA calculation. The bottom rectangular block is SiO2, and the other blocks are poly Si. Si substrate is not shown*

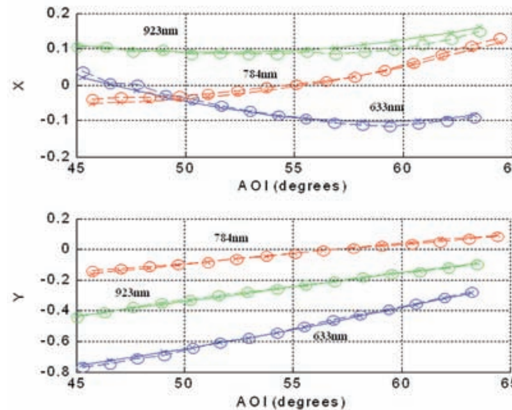

Figure 3 - *Measured versus modeled curves of FBS. X and Y are real and imaginary parts of the ellipsometer measurement.*

Optimization of the measurement setting and modeling parameters for the best performance starts with the sensitivity analysis, which estimates the changes in the raw data, delta and psi, caused by small increments of the grating model parameters – top and bottom CD, line height, etc. at different sample orientations and incidence angles. With the same algorithm, using characteristics of the measurement noise as input, one can also estimate the precision of the measured structure parameters for a given model of the grating cross-section, with various measurement configurations used to resolve the grating profile, and different combinations of fixed, or calculated parameters.

	Simulation			Measurement		
Number of lasers	CD-bottom	Poly T	CD-top	CD-bottom	Poly T	CD-top
633	0.067	0.059	0.055	0.086	0.064	0.061
633+923	0.041	0.038	0.049	0.050	0.054	0.052
633+780+923	0.035	0.035	0.044	0.033	0.045	0.047

Table 1 *- Comparison between estimated 3 sigma standard deviation (nm) from RCWA simulation and actual measurement from short term static repeats without wafer movement.*

Table 1 presents estimated repeatability of the parameters by RCWA algorithm based on the measurement noise input obtained from static repeats (precision) measurement without moving the wafer. The estimated standard deviation and actual results obtained from measurement using library lookup interpolation are very close.

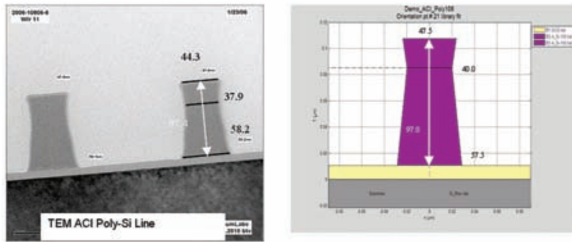

Figure 4 *- FBS result (left) compared to TEM cross section of isolated structure from the same site.*

Figure 4 illustrates the accuracy of FBS and RCWA algorithm against TEM cross section of the same site. Figure 4(a) is TEM cross section and measured dimensions, top CD, bottom CD, and poly T, are 44.3, 37.9, 58.2, and 97.4 nm respectively. Figure 4(b) is the modeled structure after non-linear regression with values very close to TEM cross section, 47.5, 40.0, 57.5, and 97.0 nm respectively. The waist of the CD is at about 80% of the height. Note, that the difference between the values obtained from FBS and dimensions marked on the TEM is smaller, or comparable to the variations between two poly Si lines imaged on the TEM picture.

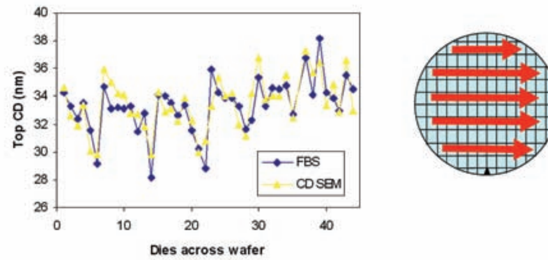

Figure 5 *- Comparison between FBS and CDSEM results across wafer.*

To verify the measured CD variation across wafer from FBS, CDSEM was used to characterize the poly CD at same measurement sites. Figure 5 shows the agreement between FBS and CDSEM at 45 dies across wafer. The measurement die sequence is also shown. The difference can be possibly caused by different calibrations of the two types of metrology tools, as well as measurement area size.

Beside the absolute accuracy, scatterometer's reproducibility and tool matching are required to meet the fab process control limit. Figure 6 shows the reproducibility of 75 measurements in a 5 day period. The 3 sigma standard deviations of bottom CD, top CD, and poly T are 0.12 nm, 0.12 nm, and 0.15 nm. The reproducibility is well within the required performance of 45 nm process node, a 3 sigma standard deviation of 0.3 nm, according to ITRS[1]. Same wafer was measured on two tools with same FBS configuration to check tool matching. Matching results from 9 dies/sites across wafer were shown in Table 2. The matching was from two tools with standard alignment and calibration, without any recipe specific offset. With the reproducibility of 0.12 nm, site to site mismatch of less than 0.35 nm, and wafer average matching of less than 0.05 nm, FBS's capability certainly met the production requirement for process node of 45 nm, outlined in ITRS[1].

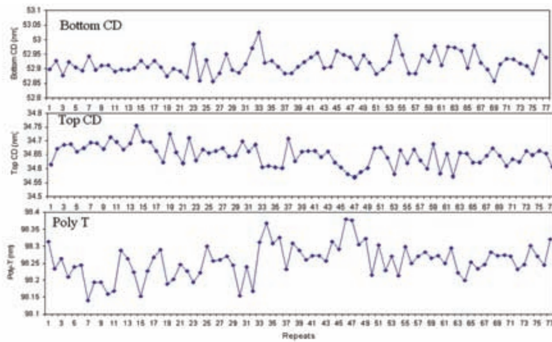

Figure 6 - 5 day reproducibility results. The 3 sigma standard deviation of bottom CD, top CD, and Poly T are 0.12, 0.12, and 0.15 nm.

Tool 1	Die 1	Die 2	Die 3	Die 4	Die 5	Die 6	Die 7	Die 8	Die 9	AVE
Bot-CD (nm)	51.14	54.85	51.05	51.69	52.1	54.25	52.88	56.16	51.94	52.9
Poly-T (nm)	98.12	98.21	97.99	98.15	98.47	99.00	98.19	98.45	98.24	98.31
Top-CD (nm)	34.43	37.15	34.85	30.50	33.43	31.81	36.62	37.58	35.92	34.70
Tool 2	**Die 1**	**Die 2**	**Die 3**	**Die 4**	**Die 5**	**Die 6**	**Die 7**	**Die 8**	**Die 9**	**AVE**
Bot-CD (nm)	50.85	55.07	51.22	51.28	51.94	54.21	53.02	55.96	52.29	52.87
Poly-T (nm)	98.11	98.10	97.98	98.13	98.70	98.96	98.05	98.44	98.11	98.29
Top-CD (nm)	34.71	37.02	34.90	30.41	33.69	31.84	36.79	37.61	35.73	34.74
Difference	**Die 1**	**Die 2**	**Die 3**	**Die 4**	**Die 5**	**Die 6**	**Die 7**	**Die 8**	**Die 9**	**AVE**
Bot-CD (nm)	-0.30	0.22	0.17	-0.40	-0.17	-0.04	0.14	-0.20	0.35	-0.03
Poly-T (nm)	0.00	-0.11	-0.01	-0.02	0.24	-0.04	-0.15	0.00	-0.13	-0.02
Top-CD (nm)	0.29	-0.13	0.05	-0.09	0.26	0.03	0.16	0.03	-0.19	0.05

Table 2 - Tool-to-tool matching of the FBS measurement on ACI structure

CONCLUSION

After cleaning (ACI) poly line structure sample was characterized using Focus Beam Scatterometer, a laser based multi-angle scatterometer. In contrast with widely used spectroscopic ellipsometry measurements at a single angle of incidence over a range of wavelengths, FBS uses simultaneous measurement at a number of discrete laser wavelengths, covering a range of incident angles. RCWA based algorithm was used for both direct non-linear regression and library lookup interpolation, to compare with FBS measurement. Samples were carefully characterized using CD-SEM and TEM cross-section as the reference metrology, to check the accuracy of the profile generated by FBS. Structure profile modeled from FBS measurement was very close to TEM cross section. Results from 45 dies across wafer showed similar trend as CDSEM. Reproducibility data of FBS was collected in a 5 day period, and the 3 sigma standard deviations of top CD, bottom CD, and poly thickness were 0.12, 0.12 and 0.15 nm. Tool matching data was also presented with wafer average mismatch within 0.05 nm, and site-to-site mismatch of less than 0.35 nm. The measurement accuracy, reproducibility, and tool matching of FBS exceeded the metrology requirement for gate control, as outlined in the ITRS[1].

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