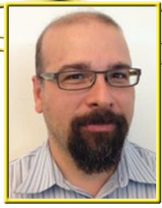
Characterization of Thin Films and Materials



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Optical Critical Dimension Metrology for Semiconductor Manufacturing

Vacuum based processes are essential in the semiconductor manufacturing process. In the simplest terms, integrated circuits are composite structures fabricated one layer at a time. Each layer is deposited as a blanket film, then patterned by removing material in selected areas. The final, three-dimensional structure, made up of insulating, conducting, and semiconducting components, forms a functional circuit. Most of the deposition and removal steps take place in a vacuum environment, which creates the physical conditions required for the process to proceed, ensures the purity of the material deposited, and removes excess process chemicals and by-products from the process chamber. Throughout its history, the semiconductor industry has defined progress almost exclusively by its ability to reduce the size of the devices it creates. Measuring critical dimensions of the component structures and controlling the manufacturing process to ensure high yields of functional devices have been a critical requirement for progress. These structures became too small to resolve with image based light microscopy decades ago. Manufacturers now rely on scatterometry for optical critical dimension (OCD) measurements. Because it is not image based, scatterometry is not constrained by the diffraction effects that limit image resolution. Furthermore, and especially important for current device architectures, scatterometry can provide three-dimensional measurements. In this article we will look at the fundamentals of OCD and provide some examples of its use on simple, representative structures. In a subsequent article we will look at OCD applications to real world structures.

For most of its history, the industry has focused on planar transistor architectures in which a gate positioned over a channel controls the flow of current through the channel between a source and a drain. A voltage applied to the gate creates an electric field (FET - field effect transistor) that excludes or permits carriers in the channel thus turning the current on or off. The source, channel, and drain are coplanar, created at the surface of a semiconductor wafer, with the gate positioned over the channel (**Figure 1**). Increasing the computing power of an integrated circuit was essentially an exercise in reducing its aerial (X and Y) dimensions.

As nominal gate lengths (nodes) approached 20 nm, planar devices encountered short channel effects, such as increasing leakage currents, that degraded their performance. To combat these ef-

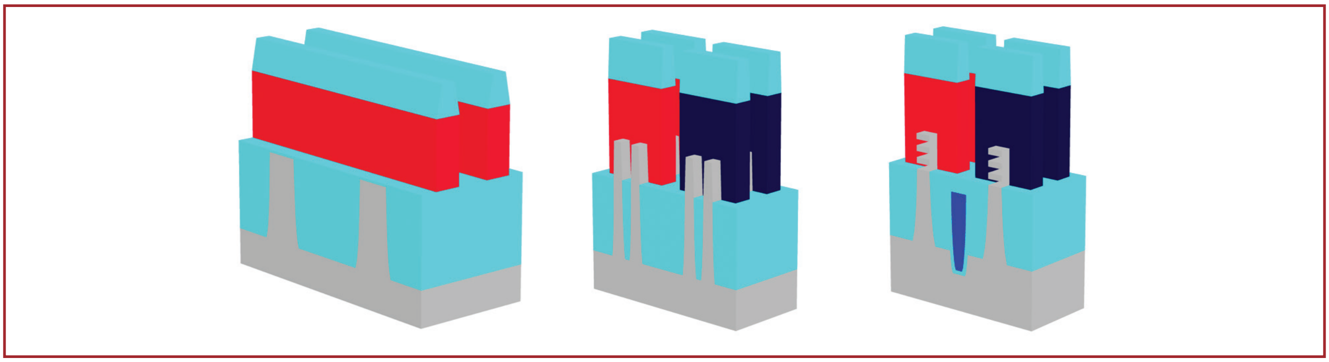

Figure 1. Comparison of (left to right) planar, fin, and gate-all-around field effect transistor architectures. https://www.overclock3d.net/news/misc_hardware/samsung_has_created_its_first_3nm_gaafet_prototypes_-_transistors_beyond_finfet/1

fects manufacturers moved to finFETs, in which the channel has the shape of a fin, surrounded on three sides by the gate (**Figure 1**). This increased the effective area of the gate in proximity to the channel. FinFET devices allowed continuing increases in computing power down to around the 5 nm node. (The node name no longer accurately reflects the gate length but is rather a convention to reflect successive generations of increasing device density and computing power.) Beyond this node, manufacturers have encountered limitations for finFETs and have had to consider other architectures. Several have chosen the gate-all-around (GAA) design in which, as the name suggests, the gate completely surrounds the channel (**Figure 1**). GAA devices promise continuing improvement in performance but include three dimensional features that greatly increase the complexity of the manufacturing process.

Process Control and Optical Metrology

Process control, ensuring that the process reliably creates functional devices with physical and electrical characteristics that fall within established process windows, is an essential part of every semiconductor manufacturing operation. Metrology, the science and practice of measuring process performance, provides the basis for process control. Just as manufacturing processes have evolved to create smaller, more complex devices, measurement technologies have had to change to monitor the new processes. Most image-based optical metrology became obsolete as critical dimensions (CD) decreased into the sub-micrometer range decades ago. The mainstay of the industry since that time has been scanning electron microscopy – specially designed for CD measurements (CD-SEM). CD-SEM is non-destructive and provides top-down, two-dimensional measurements. Cross sectional SEM (XSEM) can provide three-dimensional information, but at the cost of additional, destructive sample preparation. As device sizes have continued to decrease, dimensions have exceeded the resolution of SEM and manufacturers have adopted transmission electron microscopy (TEM). TEM can resolve individual atoms, but only at the cost of even more time-consuming, destructive sample preparation. It remains the gold-standard for accuracy and reference measurements, but its slow turnaround and low throughput are not well-suited to provide the fast response desirable for process control applications.

Although critical dimensions long ago passed beyond the resolution capability of optical imaging, other optical techniques can deliver fast, repeatable, non-destructive measurements. OCD measurements based on scatterometry derive shape, dimension and composition information from the scattering patterns observed in light that has interacted with the sample. It requires a regular array of similar features, but these are common in integrated circuits. The target may be an in-circuit feature, such as a line array, or a specially designed measurement target, typically located in the area between die on the wafer.

The simplest illustration of an OCD measurement is the interference pattern created when light falls on a regularly spaced array of lines and spaces. The spacing of the interference fringes is a function of the wavelength of the light, the configuration of the optical path, and the spacing of the lines. Because the information is carried in the phase relationships of the light waves, the technique is not constrained by wavelength-related diffraction limits on image resolution. As manufactures moved beyond the 20 nm node three-dimensional device, scatterometry entered the mainstream of process control metrology.

Scatterometry for semiconductor manufacturing process control is based on ellipsometry. An ellipsometer measures the effects of reflection (or transmission) on polarized light. Ellipsometry has long been used in semiconductor metrology to characterize thin films in multilayer stacks. It is exquisitely sensitive and accurate, capable of measuring films as thin as a single atomic layer. Ellipsometers measure a material's complex refractive index or dielectric tensor to determine fundamental physical properties. They can be used to characterize film thickness, composition, roughness, crystalline nature, doping concentration, electrical conductivity, and more.

Conventional ellipsometers look at polarized light reflected from the sample and compare it to the known polarization state of the incident light to measure the complex reflectance ratio, composed of two parameters, an amplitude component (ψ) and a phase shift difference (Δ). Spectroscopic ellipsometers use a broadband light source and measure these parameters as a function of wavelength. When used to measure thin, unpatterned films, the analysis typically assumes the sample is composed of a small number of discrete, well-defined layers that are optically homogeneous and isotropic. These assumptions are valid, and the two parameters, ψ and Δ, are sufficient, for most thin film applications.

The assumptions are not valid for scatterometry measurements of complex three-dimensional features. Conventional spectroscopic ellipsometry measures only the amount of incident p-polarized (electric field parallel to the plane of incidence) light that is reflected as p-polarized light and the amount of incident s-polarized (electric filed perpendicular to the plane of incidence) light that is reflected as s-polarized light. However, there may also be cross polarized scattering: p to s and s to p. Mueller matrix spectroscopic ellipsometry (MMSE) captures a complete description of the polarized reflection, including cross-polarization and circular polarization, in a matrix of 16 elements at each wavelength. Cross polarization carries important information about material characteristics such as symmetry, edge roughness and anisotropic optical properties. It is essential for characterizing 3D structures. The full Mueller matrix can be measured using a spectroscopic ellipsometer with dual rotating compensators (**Figure 2)**, one between the polarizer and the sample and one between the sample and the analyzer.

The utility and value of full Mueller matrix ellipsometry varies with the application. In some cases, it is essential, such as for the measurement of structural anisotropy like tilt and overlay shift. In other cases, it is not necessary, but still valuable, such as in measurements of complex structures where the additional information can help in parameter decorrelation. In the final case, the addition-

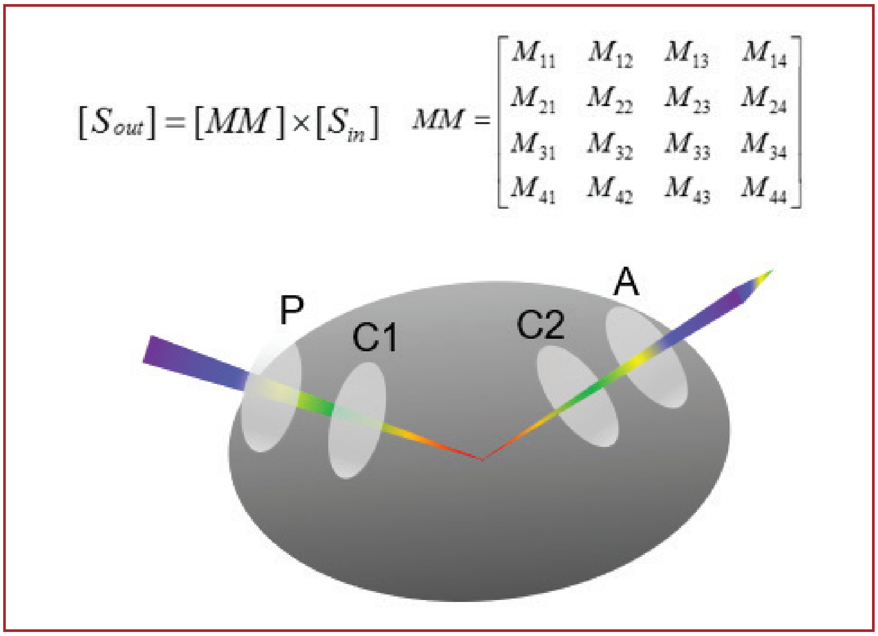

Figure 2. An ellipsometer compares incident polarized light and reflected polarized light to determine structural and material properties. With two compensators, it can acquire all 16 elements of the Mueller matrix that completely describes a reflection.

al information may be only potentially valuable but is essentially free, as when the dual compensators allow full Mueller matrix collection without using different analyzer angles.

Data Analysis – RCWA and Machine Learning

OCD is an indirect measurement. No analytical solution exists to derive the desired physical or material properties directly from the measured parameters. Rather, the process relies on the development of models and their comparison to acquired data. The classic process relies on rigorous coupled wave analysis (RCWA) to generate a set of expected Mueller matrix elements based on theoretical interactions of light with a virtual model of the structure that includes shape, dimensions, materials, optical properties, and more. To develop a measurement solution for a particular structure, parameters of the model are varied, and the resulting matrix elements recorded. Regression analysis seeks to identify key features of the matrix element spectra that vary predictably and uniquely with the parameter of interest and can therefore serve as reliable proxies. The modeling process can be time-consuming, computationally intensive, and expensive. In use, actual measurement data are compared to the modeled data to infer the desired measurement value.

Recent developments in artificial intelligence (AI) and machine learning (ML) can significantly reduce the cost and time needed to develop a solution. Machine learning essentially automates the regression process. Given an appropriate dataset of measured MMSE spectra and reference values, machine learning can often find the salient spectral features and quantify their relationships to the parameters of interest without physical modeling or structured regression analysis. ML-based solutions are unlikely to completely replace model-based solutions. Rather, they will provide a complementary capability for situations where modeling is especially challenging. The ideal space for ML solutions will be situations where modeling costs are high because of the complexity of the structure, the key parameter of interest has dominating or unique sensitivity in the signal, and reference data is abundantly available.

Examples

Figure 3 is a graphical representation of a modeled structure, in this case a gate-all-around transistor. The inner spacer, which is created at the end of each silicon channel, is a critical feature that is small and challenging to measure. But precise measurements are essential for several reasons. The size of the inner spacer determines the length of the gate. The inner spacer protects the subsequently deposited source and drain during layer release when the dummy gate is etched away and replaced with gate materials. Finally, the spacer suppresses parasitic capacitance between the source/drain and the gate.

Figure 4 shows modelled sensitivity plots for 15 of the 16 components of the Mueller matrix for the gate-all-around

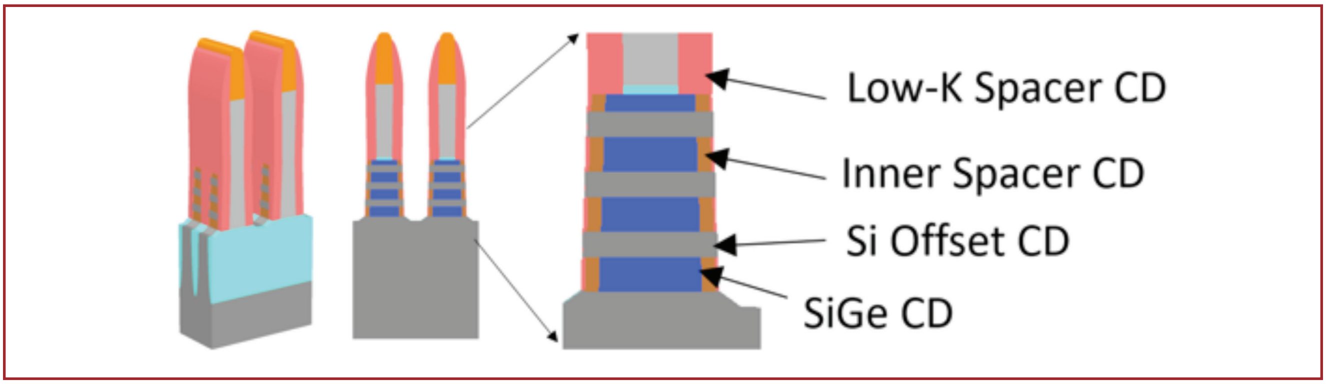

Figure 3. In a gate all around transistor the gate surrounds the channel. The dimensions of the inner spacer are critical in the performance of the transistor.

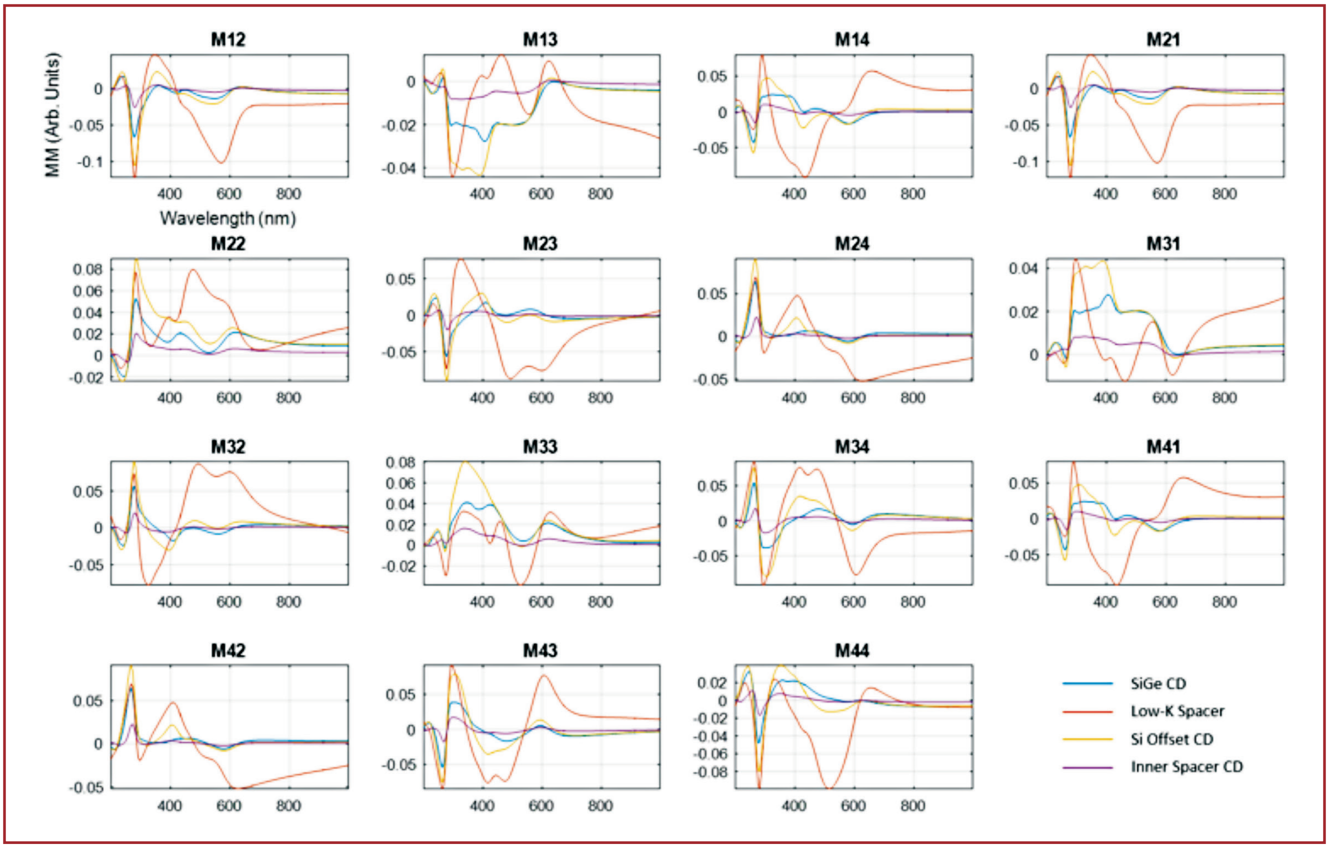

Figure 4. Modelled sensitivity curves showing the ellipsometer signal vs. wavelength for the structure illustrated in **Figure 3**. Each plot includes curves for 4 different CDs. The plots represent 15 of the 16 possible components of the Mueller matrix.

structure illustrated in **Figure 3**. Each plot includes signals for 4 different CDs: SiGE CD, Low-K Spacer CD, Si Offset CD, and Inner Spacer CD. The variability apparent among the different measurements suggests the great power of MMSE to discriminate among different features. In practice, the operator does not look at plots like these, rather, the system identifies the best signals and performs the measurement.

Two central criteria for evaluating signals are precision and correlation. Precision is a function of the sensitivity (measured change in the signal for a known change in the measured parameter) compared to the noise level of the system (random variations superimposed on the measurement). **Figure 5** shows the impact of reducing system noise on measurement precision. As noise is reduced, the signal-

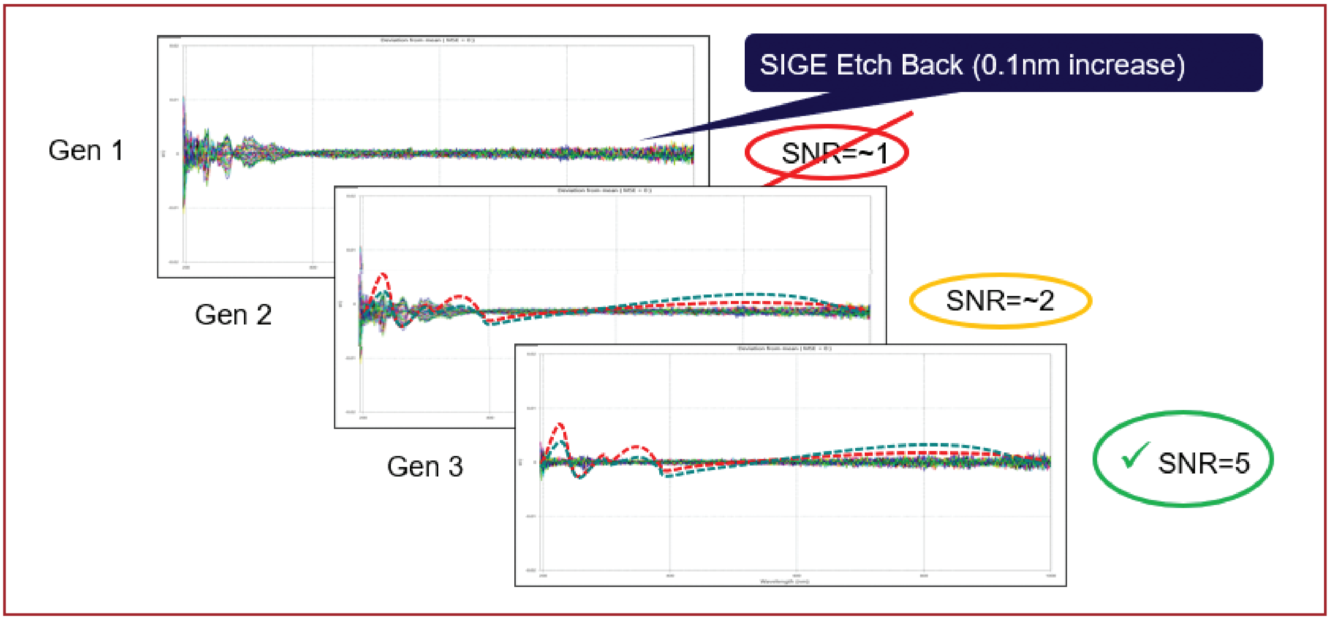

Figure 5. Decreasing noise levels over three instrument generations improve the signal-to-noise ratio (SNR) and the precision of the measurement.

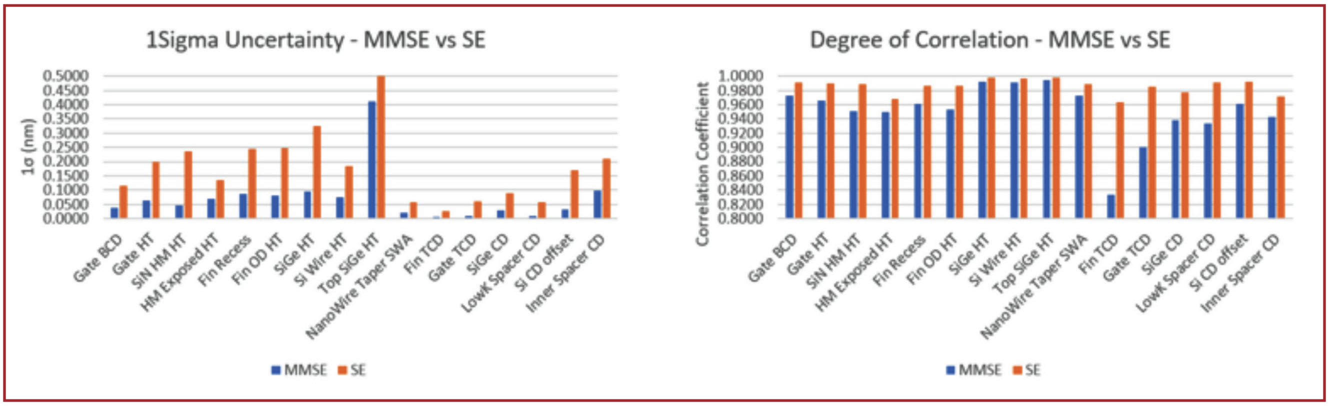

Figure 6. For each of the CDs included in this analysis, MMSE showed higher precision and lower correlation than conventional SE.

to-noise ratio increases. In this visualization, the signal (the difference between the two dashed traces) corresponds to a change of 0.1 nm in the SiGe etch back CD. Correlation refers to the ambiguity introduced by similarity among signals generated by changes in multiple unrelated parameters. In this usage, high correlation or over-correlation is undesirable, it means the signal is responding in a similar way to multiple parameters. Conversely, lower correlation indicates the response is unique to the parameter of interest. **Figure 6** compares the precision (uncertainty) and correlation of MMSE and SE measurements for several CDs.

Conclusion

As devices became too small to measure with image based optical techniques, semiconductor manufacturers turned to scatterometry based OCD for the dimensional measurements they needed to control the manufacturing process. Scatterometry is capable of measuring structures at the current node and beyond, and it can provide the three-dimensional information needed to characterize advanced device architectures. Mueller matrix ellipsometry captures a complete description of the interactions of polarized light with the structure being interrogated, providing the broadest possible data set, and increasing the likelihood of finding a component that is sensitive and unique to the parameter of interest. Advances in data analysis using machine learning and artificial intelligence can significantly reduce the time and cost of developing a measurement solution.