Semiconductor Technology from A to Z

Metrology

CD Measurement

Metrology

The critical dimension (CD) is the smallest feature width on the wafer that determines whether a device works – classically the gate length of a transistor, but also line widths, spacer thicknesses or contact hole diameters. Because the CD feeds directly into electrical parameters such as switching speed, leakage current and threshold voltage, it has to be controlled to an accuracy in the low nanometre or even sub-nanometre range.

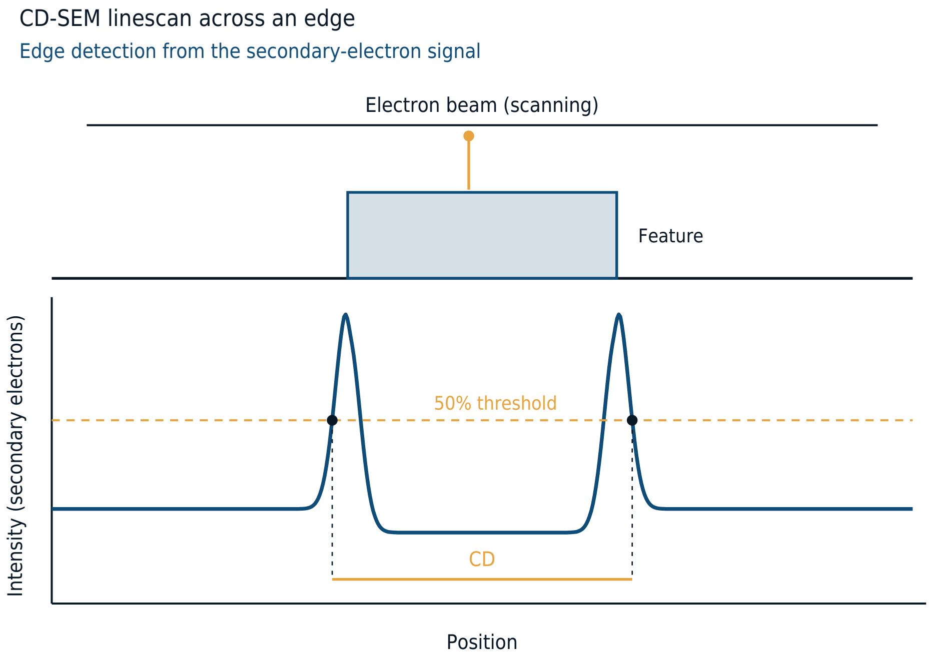
CD control takes place at several points along the process chain: directly after lithography (photoresist CD, to monitor exposure dose and focus), after etching (final CD, since the feature changes further during the etch step) and, on a sampling basis, after other critical steps. A distinction is made between the bias, the systematic deviation between the mask dimension and the actual feature, and the CD uniformity, the spread of the measured values across the wafer, from wafer to wafer and from lot to lot.

Several methods are available for the measurement itself, differing in resolution, speed and whether they are destructive. Two approaches dominate in production: direct imaging measurement using a scanning electron microscope (CD-SEM) and indirect, model-based optical measurement (OCD/scatterometry).

CD-SEM – Measurement Principle

A CD-SEM is a scanning electron microscope optimised for throughput and reproducibility and designed specifically for the automated measurement of feature widths in semiconductor manufacturing. A finely focused electron beam scans the target feature line by line; at the edges of the feature the secondary electron yield changes abruptly (edge effect), because additional electrons can escape from the sidewalls there.

Secondary electron signal while scanning across an edge



The edge position is derived from the resulting intensity profile (linescan) using a threshold algorithm, for example as the point at which the signal reaches 50 % between baseline and peak. Since the shape and height of the secondary electron peak depend on the edge profile (vertical, sloped, rounded) and on the material, different evaluation algorithms return slightly different CD values for one and the same physical edge – the choice and consistency of the algorithm is therefore part of qualifying the measurement recipe.

To avoid charging effects and beam damage on sensitive materials, particularly photoresist, a low acceleration voltage and the lowest possible dose are used. Modern CD-SEM systems achieve a repeatability in the sub-nanometre range.

Calibration and Reference Metrology

Because the CD-SEM reading depends slightly on the evaluation algorithm used and varies from tool to tool, it has to be calibrated regularly against traceable reference standards. Such reference materials carry a certified CD traceable to national standards and make it possible to record and correct systematic deviations (bias) between several CD-SEM tools in a fab (tool matching).

For absolute validation, especially for new processes or unusual feature profiles, destructive reference metrology is used in addition: a thin lamella is prepared from the wafer (for example by focused ion beam) and measured in cross section in a transmission electron microscope (TEM). The TEM cross section reveals the actual geometry including sidewall angle and profile shape and thus serves as the reference against which the faster, non-destructive CD-SEM recipe is matched.

Since a TEM cross section is laborious, slow and destructive, it is only used on a sampling basis during recipe development or when deviations occur – ongoing production monitoring is done almost exclusively with CD-SEM and/or OCD.

OCD / Scatterometry as an Alternative

Alongside the imaging CD-SEM, optical critical dimension (OCD) metrology, also called scatterometry, has become established as a fast and non-destructive complement. A periodic test structure (for example a line grating) is illuminated with polarised light at a defined angle; the structure acts as an optical diffraction grating and produces a characteristic reflection spectrum.

Unlike interferometry for film thickness measurement, this spectrum is not converted directly into a thickness but fitted against a computational model of the structure: starting from a parametric model (CD, height, sidewall angle, layer thicknesses), the expected spectrum is simulated and adjusted iteratively until it matches the measured spectrum. The model parameters of the best fit give the geometric quantities being sought.

OCD is considerably faster than CD-SEM and, in addition to the line width alone, also yields sidewall angle and height in a single measurement. In return it requires an extended periodic test structure (typically in the scribe line) and a precise optical model – if the profile changes unexpectedly, an incorrect model can produce an apparently precise but wrong CD. In practice CD-SEM and OCD are therefore used complementarily: OCD for high throughput in volume monitoring, CD-SEM for model validation and for features outside periodic test fields.

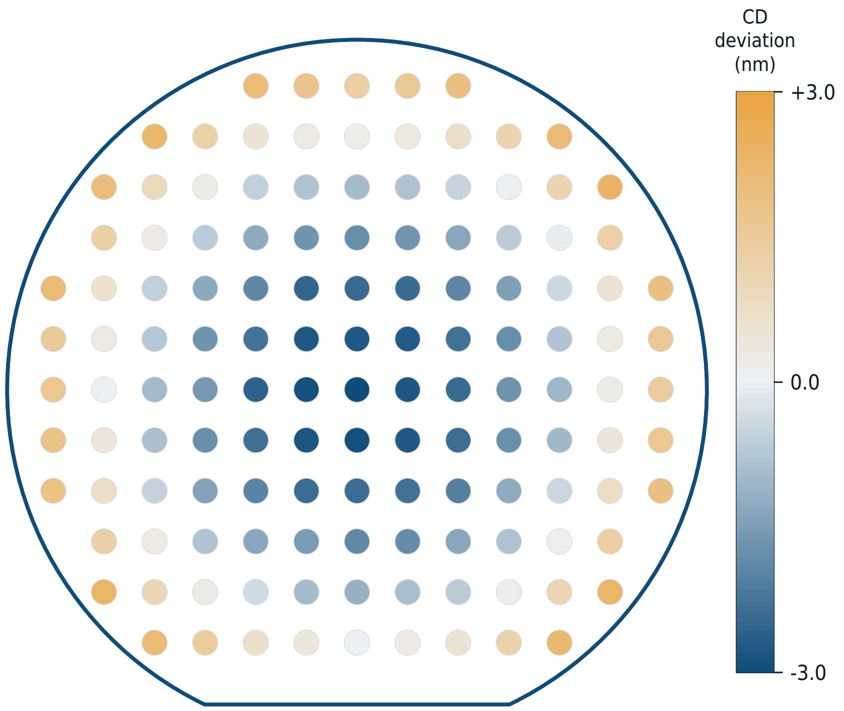
CD Uniformity and Process Control

The individual CD readings feed into statistical process control (SPC). Several levels of uniformity are distinguished: within-die uniformity (spread within a single chip), within-wafer uniformity (spread across the whole wafer, often with a characteristic edge-to-centre pattern) as well as wafer-to-wafer and lot-to-lot uniformity.

Typical CD uniformity pattern across the wafer

CD uniformity map across the wafer

Typical center-to-edge pattern of the CD deviation



If the measured CD or its spread exceeds the defined control limits, this counts as a process deviation and triggers a feedback loop to the preceding process steps: for a deviation directly after lithography, the exposure dose or focus of the scanner is readjusted (advanced process control, APC); for a deviation after etching, the etch time or gas composition. This automated feedback keeps the CD stable within the specified process window over many consecutive lots without a manual intervention being needed for every adjustment.