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Microbeam analysis — Scanning electron microscopy — Method for evaluating critical dimensions by CD-SEM

Analyse par microfaisceaux — Méthode d'évaluation des dimensions critiques par CD-SEM

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Foreword

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This document was prepared by Technical Committee ISO/TC 202, *Microbeam analysis*, Subcommittee SC 4, *Scanning electron microscopy (SEM)*.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Nanostructures need strict dimensional control to meet the demands of the semiconductor industry. Critical dimension (CD) is the minimum size of a feature on an integrated circuit that impacts the electrical properties of the device, whose value represents the level of complexity of manufacturing. At nanometer scale, measurement uncertainty control becomes more difficult with much smaller dimensions. A determination method with algorithm for accurate measurement is a key for CD valuation. CD-SEMs (critical dimension scanning electron microscopes) are one of the main tools for CD measurement in semiconductor manufacturing processes, where secondary electrons (SEs) are the signal source for CD-SEM imaging of surface structure. The CD-SEM image displays the structure geometry, but the image contrast is not a perfect representation of the structure morphology. The detected intensity linescan profile of SE signals carries the information about the sample shape and composition, beam size and shape and the information volume generated by the electron beam-solid interaction. Restricted by the physical mechanism in the processes of SE signal generation and emission, the SE signal profiles show an edge effect which leads to difficulty for accurate CD value determination with image contrast. A reliable CD determination method which bases on physical principle of SE signal emission is necessary.

Many factors, for example the specimen chemical composition, structural geometric parameters, beam conditions and other specimen/instrument factors (charging, vibration and drift), can affect CD-SEM image contrast and hence the CD measurement result. Topographic contrast in the SE mode is resulted from the enhanced SE emission from an edge as well as tilted local surface in relative to the incident beam. The quantitative description of contrast or SE intensity profile is crucial in CD metrology.

The physical mechanisms that dominate quantitative measurements by CD-SEM have been well understood. The CD determination algorithm is based on physical modelling of SE generation and emission and gives adequate consideration of the influence of various experimental factors during electron beam-specimen interaction. This document employs the model-based library (MBL) method for accurate CD determination by CD-SEM. MBL is superior to simpler, unsophisticated, arbitrary methods that disregard the physics of signal generation, and report only a meagre number, potentially with unacceptably high bias. MBL uses the whole waveform of the signal, so it can provide results with less bias and better size and shape accuracy. Once the library is set up, there is essentially no time penalty for using MBL. Construction of MBL is done with a Monte Carlo (MC) simulator which is considered as an excellent approach to take into account of every possible physical factor that may affect signal intensity and shape of linescan profiles. The library generation can be sped up tremendously by suitable multicore computing environment and MC software that is optimized for a specific measurand. Such obtained MBL relates the measured signal linescan profiles to both specimen parameters and instrumental parameters. The library database is consisted of the simulated SE linescan profiles, having a one-to-one correspondence to a specified value of parameter set. By matching the shape of SE linescan profile taking from a measured CD-SEM image with those simulated beforehand and stored in a MBL database, the best fitted CD values used in MC modelling are selected.

Microbeam analysis — Scanning electron microscopy — Method for evaluating critical dimensions by CD-SEM

1 Scope

This document specifies the structure model with related parameters, file format and fitting procedure for characterizing critical dimension (CD) values for wafer and photomask by imaging with a critical dimension scanning electron microscope (CD-SEM) by the model-based library (MBL) method. The method is applicable to linewidth determination for specimen, such as, gate on wafer, photomask, single isolated or dense line feature pattern down to size of 10 nm.

2 Normative references

There are no normative references in this document.

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
critical dimension
CD
<for a line> minimum geometrical feature size limited by the photolithography technology used for the fabrication process

3.2
CD metrology
measurement of the width of line and space for a trapezoidal line structure model

Note 1 to entry: Extended CD metrology includes the measurement of top CD, middle CD, bottom CD, height, sidewall angle, top rounding and foot rounding. Figure 1 shows schematically the definition of CDs.

Note 2 to entry: The term “top rounding” indicates a circular arc at the top corner, which is tangent to the top surface and side surface of a trapezoidal line, and whose value is represented by the circular radius.

Note 3 to entry: The term “foot rounding” indicates a circular arc at the bottom corner, which is tangent to the bottom surface and side surface of a trapezoidal line, and whose value is represented by the circular radius.

Note 4 to entry: More frequently CD represents the size of a feature on an integrated circuit or transistor that impacts the electrical properties of the device.

Note 5 to entry: Top rounding and foot rounding are not designed parameters.

3.3
critical-dimension scanning electron microscope
CD-SEM
special instrument for measuring *CDs* (3.1) of the fine patterns formed on a semiconductor wafer by producing magnified *images* (3.4) of a *specimen* (3.19) by scanning its surface with a focused electron beam

Note 1 to entry: It is mainly used in the manufacturing lines of electronic devices of semiconductors and optimized for dimensional metrology task, and differs from a general-purpose laboratory SEM in several aspects: 1. primary electron beam irradiates the sample at normal or nearly normal incidence condition; 2. the measurement repeatability around 1 % 3σ of the measurement width is guaranteed by improving magnification calibration to the maximum extent; 3. fine pattern measurements on the wafer are automated.

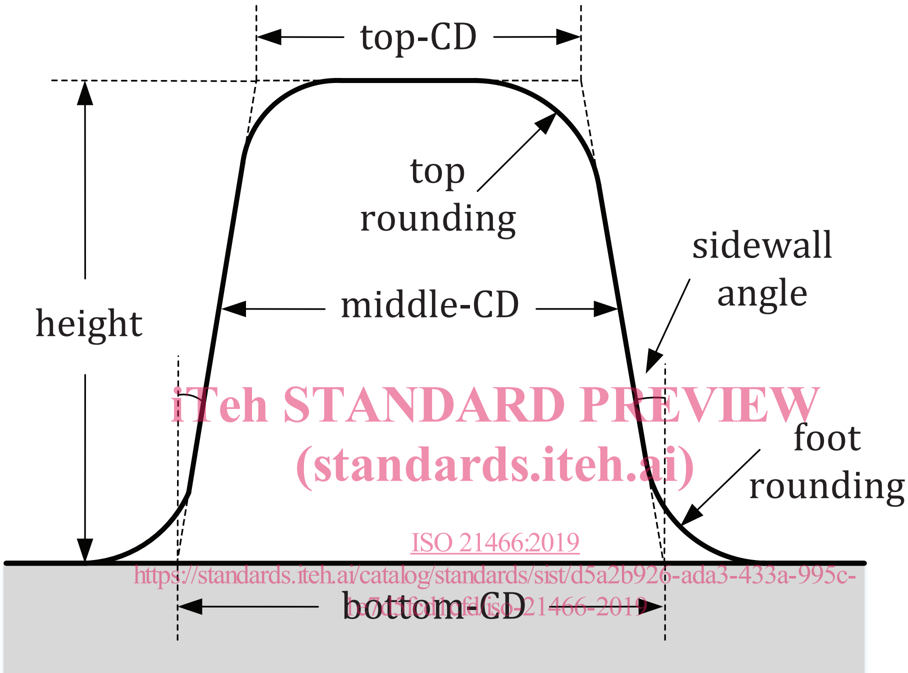


Figure 1 — Definition of CDs: top CD, middle CD, bottom CD, height, sidewall angle, top rounding and foot rounding

3.4
image
two-dimensional representation of the *specimen* (3.19) surface generated by SEM

Note 1 to entry: A photograph of a specimen taken using an SEM is a good example of an image.

[SOURCE: ISO 16700:2016, 3.2]

3.5
SEM imaging
action of forming an *image* (3.4) by a mapping operation that collects electron signals emitted from the *specimen* (3.19) surface and passes the digital signal intensity information into the storage devices

3.6
SE image
scanning (3.9) of electron beam *images* (3.4) in which the signal is derived from a detector that selectively measures *secondary electrons* (3.20) (electrons having energies less than 50 eV) and is not directly sensitive to backscattered electrons

Note 1 to entry: Intensity of digital CD-SEM image is adjusted to 8 bit (or other) depth of grayscale and does not equal to the detected physical number of secondary electron signals.

[SOURCE: ISO 23833:2013, 4.4.11, modified — Note 1 to entry added.]

3.7
electron probe
electron beam focused by the electron optical system onto the *specimen* (3.19)

[SOURCE: ISO 22493:2014, 7.1]

3.8
electron probe size
beam size
beam width
diameter of a circle that contains 50 % of the total *electron probe* (3.7) current

Note 1 to entry: For an ideal Gaussian probe shape in the radial direction:

$$\tilde{G}(r|\sigma_b)=\frac{1}{2\pi\sigma_b^2}\exp\left(-\frac{r^2}{2\sigma_b^2}\right) \quad (1)$$

the electron probe size is determined by the standard deviation (σ_b) as $d_p = 2\sqrt{2\ln 2}\,\sigma_b$, which is equal to the full width at half maximum (FWHM) of the Gaussian peak.

3.9
scanning
action of obtaining time-controlled movement of the *electron probe* (3.7) on the *specimen* (3.19) surface

3.10
linescan profile
signal intensity as function of coordinate along a straight line across an *image* (3.4)

3.11
focusing
aiming the electrons onto a particular point using an electron lens

[SOURCE: ISO 22493:2014, 3.1.4]

3.12
convergence angle
half-angle of the cone of the beam electrons converging onto the *specimen* (3.19)

[SOURCE: ISO 22493:2014, 7.1.1]

3.13
working distance
distance between the lower surface of the pole piece of the objective lens and the *specimen* (3.19) surface

Note 1 to entry: In the past, this distance was defined as the distance between the principal plane of the objective lens and the plane containing the specimen surface.

[SOURCE: ISO 22493:2014, 4.5.2]

3.14
charging effect
distortion of signal intensity in *SEM imaging* (3.5) of non-conductive *specimens* (3.19) due to accumulation of spatial charges in homogeneously distributed and hence the establishment of surface electric potential, which alters primary electron incidence (including landing energy and position) and all emitted electron signal properties

Note 1 to entry: The effect is a time dependent phenomenon and mainly related to current density and beam energy.

3.15
pixel
smallest discrete *image* (3.4) data element that constitutes an SEM image

[SOURCE: ISO 22493:2014, 5.2.4]

3.16
pixel size
length of the *pixel* (3.15), measured at a *specimen* (3.19) surface

Note 1 to entry: For a square or circular pixel, the horizontal and vertical pixel sizes should be the same.

[SOURCE: ISO 22493:2014, 5.2.5]

3.17
contrast
difference in signal intensities between two arbitrarily chosen points of interest in the *image* (3.4) field

3.18
graphics file format
archival digital format for storing the contents of the frame store

Note 1 to entry: The most popular image file formats are: bitmap (BMP), graphics interchange format (GIF), tagged image format (TIF) and joint photographic experts group (JPG). The TIF format can preserve all data and keeps the size of each pixel in its header. Consequently, this format is preferred to maintain the integrity of the images.

[SOURCE: ISO 22493:2014, 5.6.4, modified — "TIF format is the scientific format that preserves" is changed to "TIF format can preserve", admitted term "image file format" removed.]

3.19
specimen
sampled material designated to be examined or analysed

[SOURCE: ISO 22493:2014, 4.5]

3.20
secondary electron
SE
electron emitted from the *specimen* (3.19) by the excitation of loosely bound valence electrons of the specimen in electron *inelastic scattering* (3.31) events and in a cascade production process as a result of bombardment by excitation beams, e.g. electrons, ions and photons

Note 1 to entry: By convention, an emitted electron with energy lower than 50 eV is considered as a secondary electron when primary energy is above 50 eV.

3.21
SE yield
total number of *secondary electrons* (3.20) per incident electron

[SOURCE: ISO 22493:2014, 3.4.1]

3.22
SE angular distribution
distribution of *secondary electrons* (3.20) as a function of their emitting angles relative to the surface normal

[SOURCE: ISO 22493:2014, 3.4.2]

3.23
SE energy distribution
distribution of *secondary electrons* (3.20) as a function of their emitting energies above the vacuum level

[SOURCE: ISO 22493:2014, 3.4.3, modified — added "above the vacuum level"]

3.24
SE tilt dependence
effect on *secondary electrons* (3.20) of the *specimen* (3.19) tilt which accompanies a change in incident beam angle

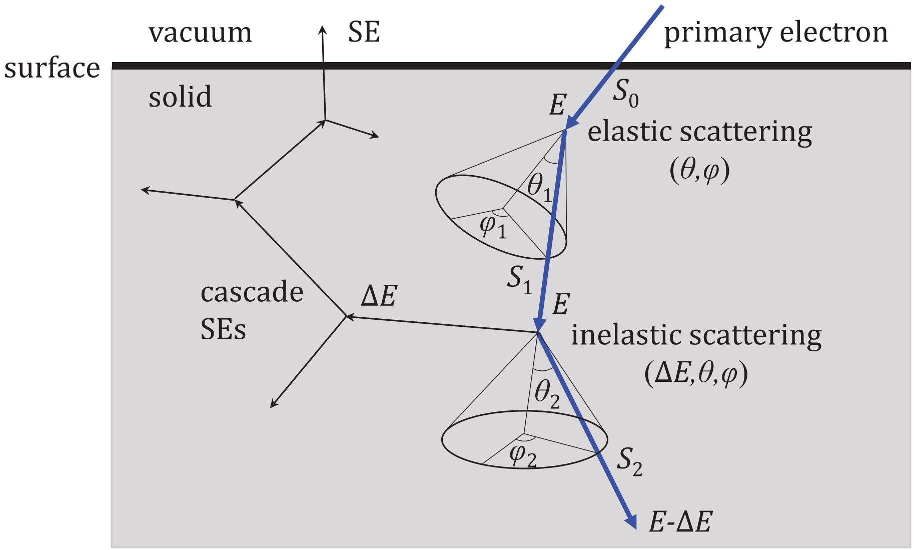
[SOURCE: ISO 22493:2014, 3.4.5]

3.25
Monte Carlo simulation
MC simulation
broad class of computational algorithms that uses statistical sampling techniques to obtain numerical results of a math model (Eckhardt 1987)

Note 1 to entry: The calculation models stochastic physical processes in the electron beam-specimen interaction and SEM image formation (Shimizu 1992; Joy 1995). The incident electron beam strikes the surface of the specimen, then a series of elastic and *inelastic scattering* (3.31) process takes place inside the specimen for the incident electrons and generated SEs. Connection of the spatial location of scattering event forms an electron trajectory. Tracking of electron trajectory is terminated when an electron is absorbed by losing its kinetic energy to below *surface barrier* (3.39) or leave from the specimen surface. Calculation includes the determination of free path as a function of energy, the outcome of a scattering event, i.e. the new direction, position and energy of a primary electron and a SE if it is generated.

Note 2 to entry: The simulation for electron beam-specimen interaction is made of the following process (Ding 1996). A primary electron enters into the specimen at an angle α of incidence, which may not be normal to the local surface even for a normal incident beam onto the substrate plane, shall suffer a scattering after flying over a distance of free path. This electron step length obeys an exponential probability distribution where the mean free path is determined by the sum of inverse electron total elastic scattering cross section and electron inelastic mean free path. By MC simulation technique a particular value of variable shall be randomly sampled from a given probability density distribution for a continuous variable or from a probability for a discrete variable with a random number uniformly distributed in the interval of 0-1. In discrete scattering model the property of scattering event being either elastic or inelastic is determined by another random number based on the proportion of elastic scattering or inelastic scattering in the total cross section. If it is elastic the scattering angle is sampled from the differential elastic scattering cross section by a random number. If it is inelastic, the associated energy loss and scattering angle are sampled from the corresponding differential or double-differential inelastic scattering cross sections. The new moving direction after scattering can then be determined to derive the updated coordinates of electron after passing by a new step length (Figure 2). Accompanied with electron energy loss in an inelastic event, one SE will be generated and its information on the energy, position and direction will be stored in a stack so that they could be read out after finishing tracing of an incident electron trajectory. All the simulated electrons, either primary or secondary, shall generate further cascade SEs along their trajectories in the solid target. If the energy of an electron reaching the surface is high enough to overcome the surface barrier it is then emitted from the local surface.

Note 3 to entry: MC simulation of SE image and SE linescan profile is performed by counting number of emitted SEs by calculating a certain number of primary electron trajectories, which are incident onto a location at specimen surface corresponding to an image pixel, and the generated cascade SE trajectories inside the specimen for a primary beam scanning the specimen surface.



Key

E electron kinetic energy

S sampled electron flight length

ΔE sampled electron energy loss in an inelastic scattering event

θ sampled electron scattering angle (polar angle) in an elastic or inelastic scattering event

φ sampled electron azimuthal angle in an elastic or inelastic scattering event

Figure 2 — Schematic diagram of Monte Carlo simulation of electron trajectory

3.26
model-based library
MBL
database of calculated SE *linescan profiles* (3.10) with a MC simulation method based on physical modelling of electron beam interaction with a *specimen* (3.19) in the *CD-SEM* (3.3) imaging process, having one-to-one correspondence between the simulated SE linescan profile and a parameter set for geometric modelling of specimen topography and beam condition

3.27
MBL simulator
specific MC simulation model and simulation software for producing a MBL database

3.28
scattering cross section
total scattering cross section
effective area that quantifies the essential likelihood of a scattering event when an incident beam strikes a target object, mathematical description of the probability of a scattering event (elastic or inelastic)

Note 1 to entry: Scattering cross-section is usually measured in units of area.

3.29
differential scattering cross section
cross section which is specified as a function of some final-state variable, such as particle angle and/or energy

3.30
elastic scattering
deflection of an electron in the Coulomb potential of an atomic nucleus where electron energy transfer is negligible and large-angle deflection is possible because electron mass is much smaller than the mass of the nucleus

Note 1 to entry: Note to entry 1: This type of electron collision is mainly responsible for the electron diffusion in a solid.

3.31
inelastic scattering
energy loss event of an electron due to its interaction with solid electrons, which resulting in an excitation of electronic state, and accompanied with small angle of deflection.

Note 1 to entry: Note to entry 1: This type of electron collision is responsible for slowing down of incident electrons and the production of SEs.

3.32
inelastic mean free path
average distance travelled by an electron through a medium before losing energy, mathematical description of the probability of an inelastic scattering event

Note 1 to entry: Inelastic mean free path is usually measured in units of length.

3.33
optical constants
refractive index $n(\omega)$ and extinction coefficient $k(\omega)$, as functions of photon energy $\hbar\omega$

3.34
dielectric function
dielectric data
complex function which describes the electrical and optical properties of a material versus wavevector q and photon energy $\hbar\omega$

Note 1 to entry: Dielectric function $\varepsilon(\omega) = \varepsilon_1 + i\varepsilon_2$ relates to refractive index $n(\omega)$ and extinction coefficient $k(\omega)$ through $\varepsilon_1 = n^2 - k^2$ and $\varepsilon_2 = 2nk$.

3.35
energy loss function
physical quantity describing electron energy loss probability or the differential inelastic *scattering cross section* (3.28), which is given via *dielectric function* (3.34) by $\mathrm{Im}\{-1/\varepsilon(q,\omega)\}$

3.36
optical energy loss function
energy loss function (3.35) at long wavelength limit, $\mathrm{Im}\{-1/\varepsilon(0,\omega)\}$

3.37
plasmon
quantum of collective electron oscillations in a metal or a semiconductor

3.38
phonon
quantum of lattice vibrations in a solid

3.39
surface barrier
potential barrier that an electron to overcome for emission from a solid into vacuum, being the electron affinity for semiconductors and insulators or the sum of Fermi energy and work function for metals

Note 1 to entry: Surface barrier is usually given in unit of eV.

4 Symbols and abbreviated terms

CD critical dimension

MBL model-based library

MC Monte Carlo

SE secondary electron

SEM scanning electron microscope/scanning electron microscopy

5 Generation of Model-based Library (MBL)

A MBL is produced by a comprehensive MC simulation with a MBL simulator for a given combination set of experimental parameters and specimen geometric parameters, which are predetermined by a MBL database developer. MBL is a set of simulated SE linescan profiles with one-to-one correspondence to a specific set of instrument- and sample-related parameters.

NOTE A MBL database developer represents an individual and/or an organization who produces a MBL database by using a MBL simulator in accordance with Clause 5.

5.1 Basic components of a MBL simulator

A complete MBL simulator is made of several components for CD-SEM image simulation (References [7][20][55][19][63]) by including electron probe model, SE signal generation model and SE signal detection model, which are then denoted as the descriptor of the MBL simulator. The values of the descriptor are noted in the MBL description document file, Model.txt.

5.1.1 Electron probe model

The electron probe intensity profile (i.e. beam shape and probe diameter) influences the CD-SEM image sharpness and hence the linescan profile. The probe diameter is broadened by the aberrations of the objective lens, which is an important instrumental parameter of MBL[50][51]. Electron intensity distribution within the beam is never ideal in practical cases. One approximation is a Gaussian shape with a constant size (spot size), another one is an “hourglass shape” beam with or without asymmetrical above- and under-focus form. Any of these can be non-perpendicular to the sample. Accounting for a couple of degrees of “stray” tilt can further improve the accuracy of MBL.

a) Gaussian beam model

The geometric theory of electron-probe formation assumes Gaussian profile of the probe shape [10][11], and the distribution in the lateral direction is given by Formula (2):

$$G(x|\sigma_b)=\frac{1}{\sqrt{2\pi}\sigma_b}\exp\left(-\frac{x^2}{2\sigma_b^2}\right) \tag{2}$$

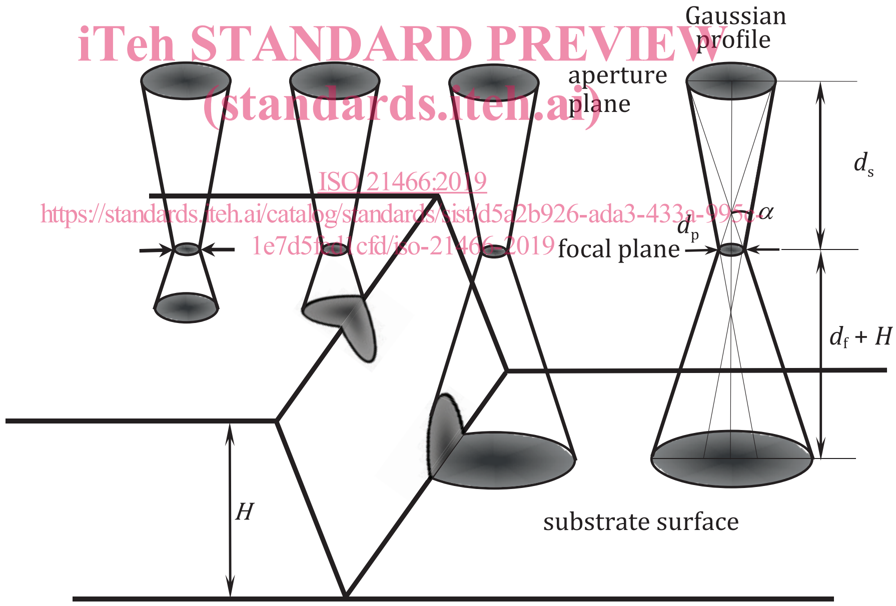
An ideal electron beam assumes the landing spot size on the surface of specimen is zero. By this modelling, specimen geometry is independent of probe size for a MBL data simulation. To minimize the library size, it is recommended to simulate SE linescan profiles only for an ideal electron beam in MBL construction; the Gaussian distributions for different probe sizes can be later used in a convolution procedure to derive linescan profiles corresponding to finite probe sizes in MBL curve matching [13].

b) Focusing beam model

This model considers an electron beam having a convergence whose angle is defined by the angular aperture[53][62]. At the focal plane electrons are distributed in a certain shape of profile not necessarily follows the exact Gaussian function, having an effective beam width in each of the x- and *y*-directions. Electrons are more divergently distributed horizontally when arriving on surface if it is away from the focal plane. By this model, the mean direction of the incident electrons is normal to the substrate plane but incident directions of individual electrons may deviate from the mean incident direction. The density distribution of electrons arriving at specimen surface is influenced by the distance away from the focus plane. Therefore, there is no exact definition of electron probe size for landing electrons as it relates to specimen topography. This makes differences on SE emission intensity for incident electrons striking on different locations of a topographic surface, e.g. between the top of the line, the sidewall, and the substrate[43][44].

The simulation of SE linescan profiles should be carried out for each value set of focusing parameters (Figure 3), i.e. the nominal probe size or effective beam width d_p (nm) which is given on the focal plane, convergence angle α (mrad), working distance d_s (mm), and defocus value d_f (nm) as the distance between the focal plane and the top surface. The focusing position is measured from the specimen top surface where it is defined as the just-focus position (i.e. $d_f = 0$), while $d_f < 0$ and $d_f > 0$ correspond to under-focus and over-focus cases, respectively, where the vertical coordinate is positive along the beam incidence direction. An incident electron trajectory with its incident direction and landing position are determined by random sampling two horizontal positions in aperture plane and focal plane from Gaussian distributions and connecting them as a straight ray towards the landing surface[62]. At the aperture plane and focal plane, the beam widths are given respectively by $d_s \tan\alpha$ and d_p. The obtained MBL curves are directly matched with the measured one without convolution.

NOTE Focusing beam model excels Gaussian beam model in accuracy of description of SE linescan profiles by adding further three parameters but enlarging greatly the MBL data file size. $d_p = 2\sqrt{2\ln 2}\sigma_b$ when $\alpha = 0$.



Key

H height of a trapezoid line

α convergence angle of incident electron beam

d_s working distance

d_f the distance between the focal plane and the top surface

d_p the effective beam width or the diameter of least confusion disc along the beam axis

Figure 3 — Schematic diagram of focusing electron probe shape at different landing positions of a line structure