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TECHNICAL REPORT

colour inside

Nanotechnologies – A guideline for ellipsometry application to evaluate the thickness of nanoscale films

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INTERNATIONAL
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NANOTECHNOLOGIES – A GUIDELINE FOR ELLIPSOMETRY APPLICATION TO EVALUATE THE THICKNESS OF NANOSCALE FILMS

FOREWORD

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IEC TR 63258, which is a Technical Report, has been prepared by IEC technical committee 113: Nanotechnology for electrotechnical products and systems, in collaboration with ISO technical committee 229: Nanotechnologies.

It is published as a double logo document.

The text of this Technical Report is based on the following documents:

DTR	Report on voting
113/548/DTR	113/563/RVDTR

Full information on the voting for the approval of this Technical Report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

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INTRODUCTION

Ellipsometry is a powerful optical technique to evaluate the dielectric properties of thin films. Ellipsometry can be used to characterize thickness, roughness, composition, crystalline nature, and other properties of nanomaterials, and is frequently used to warrant the quality and the performance of thin-film growth equipment. The signal depends on the change in the optical response of incident light that interacts with the nanomaterial being investigated.

Many current and emerging electrotechnical devices employ nanomaterials in the form of thin films. Therefore, it is important to develop a measurement protocol to evaluate the thickness of such films with sufficient accuracy. This document describes the practical considerations that need to be taken into account in using ellipsometry to evaluate the thickness of nanoscale films.

NANOTECHNOLOGIES – A GUIDELINE FOR ELLIPSOMETRY APPLICATION TO EVALUATE THE THICKNESS OF NANOSCALE FILMS

1 Scope

This document, which is a Technical Report, is focused on the practical protocol of ellipsometry to evaluate the thickness of nanoscale films. This document does not include any specification of the ellipsometers, but suggests how to minimize the data variation to improve data reproducibility.

This document includes

– outlines of the ellipsometry procedures,
– methods of interpretation of results and discussion of data analysis, and
– case studies.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/TS 80004-1, *Nanotechnologies –Vocabulary – Part 1: Core terms*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/TS 80004-1 and the following apply.

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

- ISO Online browsing platform: available at http://www.iso.org/obp
- IEC Electropedia: available at http://www.electropedia.org/

3.1 General terms

3.1.1
interlaboratory comparison
organization, performance and evaluation of measurements or tests on the same or similar items by two or more laboratories in accordance with predetermined conditions

[SOURCE: ISO/IEC 17043:2010, 3.4]

3.2 Terms specific to this document

3.2.1
polarization
direction of the electric field vector of an optical beam

Note 1 to entry: The plane of polarization is the plane containing the electric field vector and the direction of propagation of the beam.

[SOURCE: ISO/IEC 30193:2020, 3.28]

3.2.2
optical constant
refractive index $n(\lambda)$ and extinction coefficient $k(\lambda)$, as functions of wavelength λ

3.2.3
refractive index
n
ratio of the speed of electromagnetic wave in vacuum c to that in another medium v

$$n = \frac{c}{v}$$

Note 1 to entry: The refractive index shows how the speed of light is changing depending on media.

3.2.4
complex refractive index
N
index that determines the propagation of a plane electromagnetic wave in an isotropic absorbing medium expressed as

$$N(\lambda) = n(\lambda) + ik(\lambda)$$

where n and k are the real and imaginary parts, respectively

Note 1 to entry: The real n and imaginary k parts are called the refractive index and the extinction coefficient, respectively.

Note 2 to entry: Optics field convention is used for the definition of complex refractive index [1].

3.2.5
absorption coefficient
α
coefficient that describes the attenuation of electromagnetic wave intensity I_0 during propagation in absorbing media

Note 1 to entry: The electromagnetic wave intensity attenuates according to the following equation:

$$I = I_0 \exp(-\alpha x) .$$

where I_0 is the initial electromagnetic wave intensity and x is the propagation distance.

Note 2 to entry: Absorption coefficient α is related to extinction coefficient at a wavelength:

$$\alpha = \frac{4\pi k}{\lambda} .$$

3.2.6
complex dielectric constant
ε
value that indicates how atoms in a material respond when an outside electric field is applied to the material

Note 1 to entry: Complex dielectric constant is given by the equation

$$\varepsilon(\lambda) = \varepsilon_r(\lambda) + i\varepsilon_i(\lambda)$$

where ε_r, ε_i are the real and imaginary parts of complex dielectric function, respectively.

Note 2 to entry: Relationship between the complex dielectric constant and the complex refractive index obtained from Maxwell's equation is:

$$\varepsilon(\lambda) = N(\lambda)^2.$$

Note 3 to entry: Optics field convention is used for the definition of the complex dielectric constant [1].

Note 4 to entry: The terms complex dielectric function and dielectric function are used for the complex dielectric constant and dielectric constant when focusing on their wavelength or angular frequency dependence.

3.2.7
film thickness
d
distance between the top and bottom boundaries of the laminar film, where each boundary is determined as the interface at which the refractive index changes

3.2.8
Brewster's angle
angle of incidence at which there is no reflection of p-polarized light at an uncoated optical surface

4 Measurement of ellipsometry

4.1 General

The practical protocol of ellipsometry is well-established.

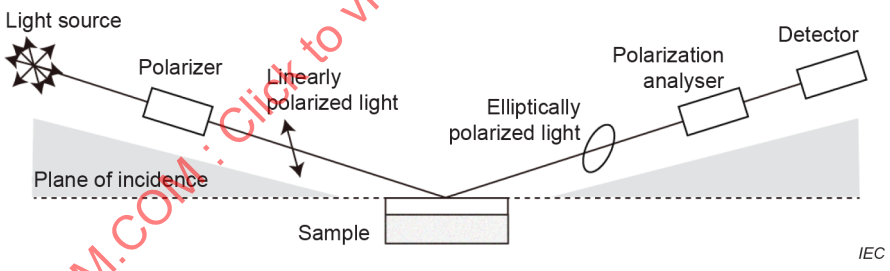

Figure 1 – Primary structure of ellipsometry measurement

Ellipsometry measures a change in polarization as light reflects from a sample. The polarization change is represented as an amplitude ratio, Ψ, and the phase difference, Δ. The basic components of the ellipsometry measurement are a light source, a polarizer, a polarization analyser and a detector, as shown in Figure 1. See references [2][1] and [3] for principles of ellipsometry.

1 Numbers in square brackets refer to the Bibliography.

4.2 Measurement procedure

4.2.1 Sample preparation for system check

Before the actual sample measurement is performed, it is necessary to check the system's accuracy. To make it possible, a reference sample with known thickness and/or refractive index should be used. The reference samples such as thermally oxidized SiO_2 on Si are available.

Ellipsometry is very sensitive to physical and chemical properties of the thin film material, its surface and the properties at the film–substrate interface.

4.2.2 Experimental procedure for system check

The general protocol of ellipsometry measurement is standardized to evaluate thin films.

– Step 1: Positioning of the reference sample on the stage.
– Step 2: Adjustment of the height and tilt.
– Step 3: Measurement of the reference sample.
– Step 4: Data analysis.
– Step 5: Result of thickness or refractive index should be within 1 % of the guaranteed values.
– Step 6: If the obtained result fulfils the condition of step 5, start to measure the test sample. If not, the system needs additional check.

It is advisable to check the system at the required angle of incidence.

4.2.3 Sample handling

Ellipsometry is very sensitive to physical and chemical properties of the sample's surface, so it is advisable to keep the sample in a clean and dry place after the preparation. Touching and scratching the surface should be avoided, because non-professional cleaning might affect the surface state and therefore change the result.

4.2.4 Experimental procedures

The general protocol of ellipsometry measurement is as follows.

– Step 1: Positioning of the sample on the stage.
– Step 2: Adjustment of the angle of incidence, height and tilt.
– Step 3: Measurement of the sample.
– Step 4: Data analysis.
– Step 5: Validation of analysis result.

NOTE This protocol is valid for non scattering and isotropic sample planes.

In order to minimize the data variation, the following practical recommendations apply.

1) The ellipsometry measurement should be done at an angle of incidence close to the Brewster's angle of the substrate.
2) The ellipsometry measurement should be done over a measurement wavelength range as wide as possible. For example, if there is absorption in the visible range, it needs to be measured including the near-infrared range.
3) The fitting analysis should be performed by changing the initial value of the film thickness and the type of dispersion formula at the time of analysis. The comparison should be done to confirm that equivalent results can be obtained. See Annex A.

5 Reporting data

– Documentation of the environment (temperature, humidity, cleanroom or normal ambient).

– Instrument used, including specification of the measurement programs and settings.

– Visual appearance of samples (to document any dust, cracks, moisture or other noticeable visual items).

– Individual measurement values.

– Calculated averages if applicable.

6 Data analysis / interpretation of results

6.1 General

Ellipsometry measures changes in light polarization to evaluate the material properties, such as film thickness and dielectric constants. In spectroscopic ellipsometry, the measured spectra are analysed by using the model fitting. Generally, in the case of nanomaterials, there is typically a surface oxide, roughness, and intermixing at the heterointerface of the sample. The common procedure to deduce material properties from ellipsometry measurements is shown in Figure 2. Evaluations of nanomaterial characteristics by using the ellipsometry measurements are shown in Annex B.

In the case of ellipsometry measurements, the intensities or polarization state ratios (complex relative amplitude attenuation) are measured and the ellipsometric angles, that is ellipsometric transfer quantities Ψ and Δ, are calculated. No direct access exists to the parameters in which we are usually interested, such as the dielectric functions (ε), refractive indices (N), compositions and film thicknesses (d).

In general, for any planar structure on the substrate, Ψ and Δ could be calculated if thicknesses and refractive indices are known. On the other hand, for the inverse case, even if Ψ and Δ are known, d and N could not be directly calculated. In order to obtain d and N for each layer, modelling is required. The modelling approach is based on the assumption that the measured $\Psi(\lambda)$ and $\Delta(\lambda)$ change at each wavelength according to dispersion law.

Determination of material properties could be done by describing the fundamental response of a material to an applied electromagnetic field. Each material has unique energy dependence of dielectric function ε. In the visible-near UV range, dielectric response is determined almost entirely by the electronic properties of a material.

A mathematical description of the dielectric properties of a material, as well as its optical properties, as a function of energy (wavelength) is provided by dispersion law (formulae) and can be divided into four categories:

1) empirical formulas;
2) classical dispersion models (harmonic oscillator treatment);
3) models based on quantum mechanical calculations;
4) point-by-point calculations.

The flow of spectroscopic ellipsometric data analysis procedure is shown in Figure 2.

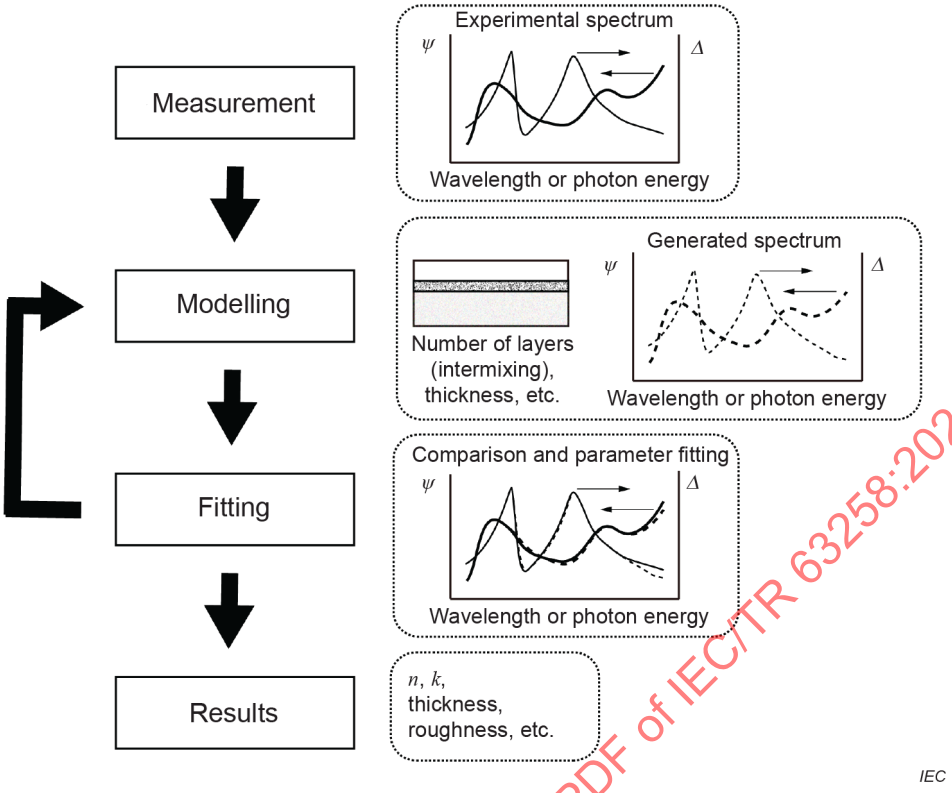

Figure 2 – Flow chart of the ellipsometry data analysis

6.2 Setting analysis model

Ellipsometric modelling can be divided into four major steps:

1) sample structure definition;
2) sample simulation;
3) choice of variables and fitting;
4) a check of model reliability.

In most general cases, to build a sample model one has to define the following unknowns:

a) substrate dielectric function;
b) each layer's thickness;
c) each layer's dielectric function and/or composition;
d) overlayer thickness;
e) overlayer dielectric function and/or composition.

Remember that complex dielectric functions and complex optical constants are related by Equation (1) as follows:

$$\varepsilon(\lambda) = N(\lambda)^2 \tag{1}$$

Using the constructed optical model, calculated data points ($\Psi(\lambda)$ and $\Delta(\lambda)$) are obtained.

For example, when analysing a SiO_2 film (for example, with the thickness of 50 nm as the estimated value) on a Si substrate, specify the material data file (complex dielectric function of Si from the library) of Si on the substrate and SiO_2 (classical model) on the first layer film. The expected film thickness of SiO_2 is set to 50 nm. All the parameters set in this model are used as initial values during the fit (analysis).

6.3 Data fitting and validation of analysis result

6.3.1 General

Two sets of data points [measured, $\Psi_{Mes}(\lambda)$, $\Delta_{Mes}(\lambda)$ and calculated, $\Psi_{Cal}(\lambda)$, $\Delta_{Cal}(\lambda)$] are numerically compared and the fitting of parameters is performed to minimize the "mean square error (MSE)", χ^2.

After sample simulation has been satisfactorily completed, you need to use measured ellipsometric data to improve the nominal model. In other words, you need to find the set of model parameters (d_1, $N_1(\lambda)$, d_2, $N_2(\lambda)$, …, d_j, $N_j(\lambda)$ …), where the subscripts indicate the j-th layer of the film, that yields calculated Ψ and Δ values as close to the measured values as possible. In order to fit the model to the data, a means of estimating the error between calculated and measured data points is required. For example, MSE to the data can be defined as follows [4]:

$$\chi^2 = \frac{1}{2M-P}\sum_{i=1}^{M}\left\{\frac{\left(\Psi_{Mes}(\lambda_i)-\Psi_{Cal}(\lambda_i)\right)^2}{\sigma_\Psi(\lambda_i)^2}+\frac{\left(\Delta_{Mes}(\lambda_i)-\Delta_{Cal}(\lambda_i)\right)^2}{\sigma_\Delta(\lambda_i)^2}\right\}, \quad (2)$$

where

M is the number of measured data points;

P is the number of fitting parameters;

$\sigma_\Psi(\lambda_i)$ and $\sigma_\Delta(\lambda_i)$ are the experimental errors of $\Psi_{Mes}(\lambda)$ and $\Delta_{Mes}(\lambda)$, respectively.

Since actual measurement and fitting are done in several different ways, one can also define alternative MSE for the $\Psi(\lambda)$ and $\Delta(\lambda)$, or any other representation of the given data [5].

When it would not be realistic to determine each $\sigma_\Psi(\lambda_i)$ and $\sigma_\Delta(\lambda_i)$ experimentally, those can be fixed for all data points. By minimizing χ^2 we are fitting the calculated data to the measured values, so as χ^2 becomes smaller, the model fit improves. In this case, the absolute value of χ^2 does not just measure the goodness of fit. If $\chi^2 \leq 1$, $\sigma_\Psi(\lambda_i)$ and $\sigma_\Delta(\lambda_i)$ have been set too large. If $\chi^2 > 1$, $\sigma_\Psi(\lambda_i)$ and $\sigma_\Delta(\lambda_i)$ might have been set too low. If $\chi^2 >> 1$, the calculated model does not fit the data. Because of the simplified calculation of χ^2 (i.e. using a fixed $\sigma_\Psi(\lambda_i)$ and $\sigma_\Delta(\lambda_i)$), you need to take into account the "look" of the fit and the calculated χ^2 value to determine its goodness.

At the end of fitting, the reliability of the modelling results needs to be checked.

– Check the final MSE. Large values of the final MSE usually indicate a poor fit to the measured data.

– Visually compare the measured data and the final best fit calculated data.

– Check if your result is physical and corresponds to the information you have. You can also compare with other techniques.

– Check the error of fitting parameters: large values usually indicate poor fit to the measured data.

NOTE 1 In some cases, the experimental value of the reference sample is used instead of the calculated data point.

NOTE 2 The parameter value can be fixed at a physically reasonable value to improve the goodness of the fitting.

6.3.2 Data analysis method 1 – Dispersion law (Cauchy model) [6]

Set the configuration of the analysis target (optical model). For example, when analysing a SiO_2 film (for example, with the thickness of 50 nm as the estimated value) on a Si substrate, specify the material data file of Si on the substrate and SiO_2 (classical model Cauchy) on the first layer film. The expected film thickness of SiO_2 is set to 50 nm. The analysis model set here is used as an initial value at the time of analysis.

The Cauchy model approximates the chromatic dispersion of the optical constants of transparent substances with the following Cauchy formula.

$$n(\lambda) = C_0 + C_1/\lambda^2 + C_2/\lambda^4 + \ldots \quad (3)$$

Here C_0, C_1 and C_2 are coefficients of optimization, and are usually used up to the third term.

This approximation formula is applied in the normal dispersion region of the transparent substance. It is used as a material data file showing wavelength dispersion of a transparent film such as SiO_2.

6.3.3 Data analysis method 2 – Sellmeier equation model (transparent material) [7]

The Sellmeier equation model is an empirical relationship between refractive index and wavelength for a particular transparent medium. The usual form of the equation for glasses is

$$n(\lambda)^2 = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3} \quad (4)$$

where $B_{1,2,3}$ and $C_{1,2,3}$ are the constants to be determined by the fitting process.

If all terms are specified for a material, at long wavelengths far from the absorption peaks the value of n tends to $n \approx \sqrt{1+\sum_i B_i} \approx \sqrt{\varepsilon_r}$, where ε_r is the relative dielectric constant of the medium.

The Sellmeier equation can also be given in another form:

$$n(\lambda)^2 = A + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} \quad (5)$$

Here, the coefficient A is an approximation of the short-wavelength (ultraviolet) absorption contributions to the refractive index at longer wavelengths. Other variants of the Sellmeier equation exist that can account for a material's refractive index change due to temperature, pressure, and other parameters.

6.3.4 Data analysis method 3 – Drude dispersion model (conductive material) [8], [9]

Drude's model (1900) is based on the kinetic theory of electrons in a metal which assumes that material has motionless positive ions and a non-interaction electron gas. This simple model uses classical mechanical theory of free electron. It was constructed in order to explain the transport properties of conduction electrons in metals (due to intra-band transitions in a quantum-mechanical interpretation), conductive oxides and heavily doped semiconductors. The real and imaginary parts of the dielectric function are given by:

$$\varepsilon_r(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + \Gamma^2} \tag{6}$$

and

$$\varepsilon_i(\omega) = \frac{\omega_p^2 \cdot \Gamma}{\omega \cdot (\omega^2 + \Gamma^2)} \tag{7}$$

where Γ is the damping factor and ω_p is the plasma frequency.

The behaviour of the Drude dielectric function can be described as follows.

If ω is sufficiently smaller than ω_p the real part of ε is negative: any electrical field cannot penetrate the metal that is totally reflective. The optical constants of the material are complex.

If ω is close to ω_p the real part of the dielectric function is zero. This means that all electrons oscillate in phase throughout the material propagation length.

If ω is sufficiently larger than ω_p the reflectivity decreases and the metal becomes transparent. The refractive index of the material is almost real.

6.3.5 Data analysis method 4 – Dispersion law (classical model / Lorentz model) [8], [9]

The Lorentzian dispersion formula comes from the solution of the equation of an electron bound to a nucleus driven by an oscillating electric field. The response is equivalent to the classical mass on a spring which has damping and an external driving force. It generates damped harmonic oscillators.

$$\varepsilon(\omega) = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty) \cdot \omega_t^2}{\omega_t^2 - \omega^2 + i \cdot \Gamma_o \cdot \omega} + \sum_{j=1}^{2} \frac{f_j \cdot \omega_{oj}^2}{\omega_{oj}^2 - \omega^2 + i \cdot \gamma_j \cdot \omega} \tag{8}$$

The Lorentz oscillator model works well for insulators such as SiO_2, and semiconductors above the band gap.

In case of existence of free electrons, Drude component could be added to Equation (3).

$$\varepsilon = \varepsilon_\infty + \frac{(\varepsilon_s - \varepsilon_\infty) \cdot \omega_t^2}{\omega_t^2 - \omega^2 + i \cdot \Gamma_o \cdot \omega} + \frac{\omega_p^2}{-\omega^2 + i \cdot \Gamma_D \cdot \omega} + \sum_{j=1}^{2} \frac{f_j \cdot \omega_{oj}^2}{\omega_{oj}^2 - \omega^2 + i \cdot \gamma_j \cdot \omega} \tag{9}$$

where

ε_∞, ε_s are the high frequency and static dielectric constants, respectively;

Γ_o, Γ_D, γ_j are the damping factors (γ_j, Γ_o, Γ_D > 0);

f_j is the oscillator strength parameter;

ω_{oj}, ω_t, ω_p are the oscillator, transverse and plasma frequency, respectively.

6.3.6 Data analysis method 5 – Forouhi-Bloomer dispersion model [10], [11]

The Forouhi-Bloomer dispersion model is applicable to amorphous semiconductors and dielectrics and is based on the quantum-mechanical theory of absorption. It takes into account the optical band gap in the inter-band region. It is supposed that the valence and conduction bands are parabolic and are separated by a forbidden band whose width is E_g. Peaks that can be seen in the optical spectrum correspond to transitions of electrons between two states. For an amorphous material, a single peak in the optical spectrum refers to the transition between the bonding state in the valence band and the anti-bonding state in the conduction band.

For crystalline semiconductors, dielectrics and metals, several peaks can be observed, indicating the transitions occurring between the critical point in the valence and conduction bands.

Optical properties depend on inter-band transitions of electrons that are related to phonon absorption. Equation (10) derives from the quantum expression:

$$\alpha(\omega) = \lim_{\Delta x \to 0}\left[-\frac{1}{I}\cdot\frac{\Delta I}{\Delta x}\right] = \frac{\Theta(\omega)\cdot\Phi(\omega)}{I_0} = \frac{2\cdot\omega\cdot k}{c} \tag{10}$$

where

$\Theta(\omega)$ is the total number of ways a photon is removed from the incident intensity in a unit volume and a layer of infinitesimal propagation distance Δx;

$\Phi(\omega)$ is the transition probability rate at which a photon is absorbed from the incident intensity in the frequency range [ω; $\omega + d\omega$];

I_0 is the incident photon intensity.

6.3.7 Data analysis method 6 – Tauc-Lorentz dispersion model (amorphous materials) [12], [13]

Jellison and Modine developed this model in 1996 using the Tauc joint density of states and the Lorentz oscillator. Here the imaginary part of the dielectric function is given by the product of the imaginary part of Tauc's dielectric function (1966) and the Lorentz one.

$$\varepsilon_{i,\,TL}(E) = \varepsilon_{i,\,L} \times \varepsilon_{i,\,T} = \begin{cases} \dfrac{1}{E}\dfrac{AE_0C\left(E-E_g\right)^2}{\left(E^2-E_0^2\right)^2+C^2E^2} & \text{for } E > E_g \\ 0 & \text{for } E \le E_g \end{cases} \tag{11}$$

where

E is a photon energy;

E_0 is the peak transition energy;

E_g is the optical bandgap;

A is a parameter which has a unit of energy;

C is the broadening term.

The real part of the dielectric function is derived from the expression of the imaginary part using the Kramers-Kronig integration.

$$\varepsilon_r(E) = \varepsilon_r(\infty) + \frac{2}{\pi} \cdot P \cdot \int_{E_g}^{\infty} \frac{\xi \cdot \varepsilon_i(\xi)}{\xi^2 - E^2} d\xi \quad (12)$$

Where P is the Cauchy principal value containing the residues of the integral at poles located on the lower half of the complex plane and along the real axis. The Tauc-Lorentz model works particularly well for amorphous materials exhibiting an absorption (e.g. absorbing dielectrics, semiconductors, polymers). On the other hand, the Tauc-Lorentz model requires the imaginary part to be zero for energies less than the band gap. Consequently, the Tauc-Lorentz model does not take into account intra-band absorption: any defect or intra-band absorption increases the imaginary part below the band gap and generates bad fits in that region.

During the past several decades, many dispersion models have been published, most of them based on the Kramers-Kronig relation and strongly connected with the electronic energy-band structure of material. In the case of compound semiconductors, useful formulas were published [14], [15].

Annex A
(informative)

Case study: Interlaboratory comparison by using SiO_2/Si samples

For the interlaboratory comparison, there should be ideally several SiO_2 samples with a range of thicknesses, with ideally 5 to 10 samples, where the largest thickness is about a factor of 10 higher than the smallest thickness. See references [16] and [17] for a typical interlaboratory comparison of SiO_2/Si samples among organizations including national metrology institutes. In the case of interlaboratory comparison, it is possible to draw bilateral correlation graphs between the participants. The correlation coefficients, the slopes and the intercepts of the linear regression analysis will give a good and statistically underpinned indication of the quality of each measurement series and point towards potential causes for deviations and improvements. In order to minimize the data variation, the experimental procedures with the practical recommendations shown in 4.2.4 are effective and useful. It should be noted, however, that the measurement accuracy generally degrades greatly when the thickness of the film becomes extremely thin [16], [17].

An example report form is shown in Figure A.1 and an example of the results is shown in Figure A.2. The sample used for the interlaboratory comparison is shown in Figure A.3.

Measurement place:
Name of measuring device (manufacture, model):
Name of operator:

Measurement date: Year Month Day Time

Temperature: XX,X °C Humidity: YY,Y %

	Sample: Thermal oxidation SiO_2				
Evaluation value	Film thickness (nm)	n	k	χ^2	Measurement angle (θ)
Measurement point 1					
Measurement point 2					
Measurement point 3					
Measurement point 4					
Measurement point 5					

Fitting method	

Note: Example of measurement point's choice (white ellipse) in the centre (15 mm square) of wafer.

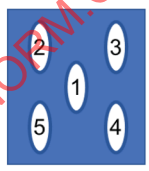

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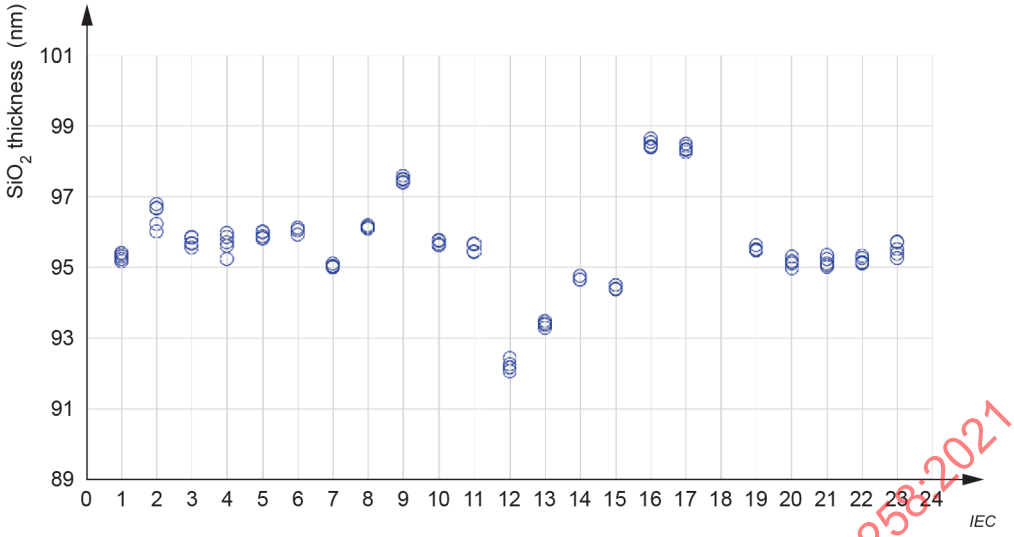
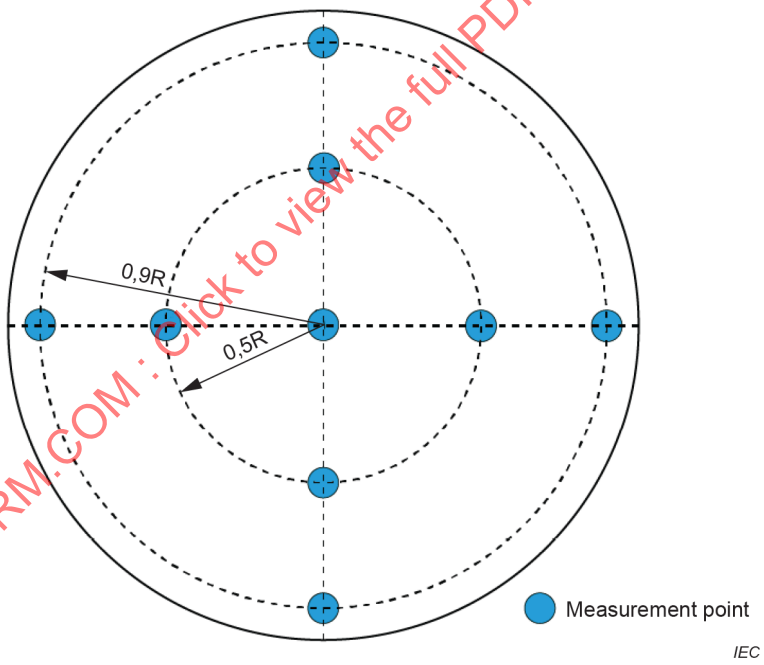
Figure A.1 – An example of the report form of ellipsometry measurements



The sample was the thermally-oxidized SiO_2 thin film on the Si substrate. Thermal dry oxidation was performed in the furnace (Tokyo Electron, XL-7) at 1 100 °C for 40 minutes. The thickness was (95,1 ± 3,9) nm, which was certified by using X-ray reflectivity. (NMIJ Certificate No.163065). The horizontal axis shows the participating laboratory's number.

Figure A.2 – An example of the results of the interlaboratory comparison



The measurement points are shown. The size of the wafer was about 10 cm in diameter.

Figure A.3 – The wafer-shaped sample used for the interlaboratory comparison