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DETAILED INFORMATION

Used Instrument for Certification

- Description : KRISS Reference Spectroscopic Ellipsometer
- Manufacturer & model : KRISS & RTSE-VA-VSH-UV~NIR-1000

Certification Method

- Preparation and certification of reference materials used for optical measurement of thickness of a silicon nitride layer on silicon [R-207-018]

Certification Traceability of Used Instrument

- These certified results have traceability to the definition of the base unit of the international system (SI) of units, through the calibrated KRISS reference spectroscopic ellipsometer.

Conditions on Measurement and Analysis

- Measurement conditions (level of confidence: 68 %, coverage factor: $\kappa = 1$)
 - Measurement wavelength(λ) : (229.5~989.5) nm \pm 0.5 nm
 - Angle of incidence(ϕ) : (65.000, 70.000, 75.000)° \pm 0.006°
 - Measurement position : Inside a 2.5 cm x 2.5 cm square area centered on the sample
- Analysis model structure : (Air)/(silicon nitride film layer)/(single crystal silicon substrate)

Certification Results

- Average value of the observed spectrum of ellipsometric transfer quantities(ETQs)
 - Structure of the attached observed data file: 0000-00000-000_Certified Values of ETQs.dat

1 st Column	2 nd Column	3 rd Column	4 th Column	5 th Column	6 th Column
λ / nm	ϕ / °	Average of N_m values	Type A standard uncertainty of N_m	Type B standard uncertainty of N_m	Combined standard uncertainty of N_m
7 th Column	8 th Column	9 th Column	10 th Column	11 th Column	12 th Column
Average of C_m values	Type A standard uncertainty of C_m	Type A standard uncertainty of C_m	Combined standard uncertainty of C_m	Average of Ψ values / °	Type A standard uncertainty of Ψ /
13 th Column	14 th Column	15 th Column	16 th Column	17 th Column	18 th Column
Type B standard uncertainty of Ψ /	Combined standard uncertainty of Ψ /	Average of Δ values / °	Type A standard uncertainty of Δ /	Type B standard uncertainty of Δ /	Combined standard uncertainty of Δ /

☞ Ellipsometric Transfer Quantity(ETQ): $\{N_m [= \cos(2\Psi)], C_m [= \sin(2\Psi)\cos\Delta]\}$ or $\{\Psi, \Delta\}$.

☞ Example) Certified average value of each ETQ observed at a measurement wavelength of (250.3 \pm 0.5) nm and an incident angle of (65.000 \pm 0.006)°, [level of confidence: 95 %, coverage factor: $\kappa=2$].

$$\begin{aligned}
 \cdot \overline{N_m} &= \underline{0.2206 \pm 0.0010} \\
 \cdot \overline{C_m} &= \underline{-0.0032 \pm 0.0043} \\
 \cdot \overline{\Psi} &= \underline{(38.63 \pm 0.03)^\circ} \\
 \cdot \overline{\Delta} &= \underline{(90.19 \pm 0.26)^\circ}
 \end{aligned}$$

- Analyzed results of thin film layer thickness and complex refractive indices of each layer.
 - Thickness of thin film layer : $(11.34 \pm 0.10) \text{ nm}$ (level of confidence: 95 %, coverage factor: $\kappa=2$)
 - Structure of the attached analyzed data file: 0000-00000-000_Certified Values of Complex Refractive Indices.dat (level of confidence: 68 %, coverage factor: $\kappa=1$)

1 st Column	2 nd Column	3 rd Column	4 th Column	5 th Column
WL / nm	Refractive index of thin film layer	Extinction coefficient of thin film layer	Combined standard uncertainty of refractive index of thin film layer	Combined standard uncertainty of extinction coefficient of thin film layer
6 th Column	7 th Column	8 th Column	9 th Column	
Refractive index of c-Si substrate	Extinction coefficient of c-Si substrate	Combined standard uncertainty of refractive index of c-Si substrate	Combined standard uncertainty of extinction coefficient of c-Si substrate	

☞ In the complex refractive index, which is a complex number, the real part is the refractive index $[n(\lambda)]$, and the imaginary part is the extinction coefficient $[k(\lambda)]$.

☞ Example) Analyzed results of complex refractive index of each layer at a measurement wavelength of $(250.3 \pm 0.5) \text{ nm}$ (level of confidence: 68 %, coverage factor: $\kappa=1$)

- Refractive index of thin film layer(n_f) : 2.171 ± 1.388
- Extinction coefficient of thin film layer(k_f): 0.057 ± 0.147
- Refractive index of c-Si Substrate(n_s) : 1.631 ± 0.020
- Extinction coefficient of c-Si Substrate(k_s): 3.689 ± 0.044

- The thickness of the thin film layer was determined from the ellipsometric transfer quantity spectrum observed when fixed input values for the complex refractive indices of each layer were adopted as the reference values below in the analysis model.
 - Thickness of thin film layer : $(11.33 \pm 0.84) \text{ nm}$ (level of confidence: 95 %, coverage factor: $\kappa=2$)

☞ The complex refractive index ($\tilde{N}_f = n_f - ik_f$) value of the thin film layer is obtained using the relation of $\tilde{N}_f = \sqrt{\epsilon_f}$ from the Tauc-Lorentz dispersion function ($\epsilon_f = \epsilon_{f,1} - i\epsilon_{f,2}$) below.

$$\epsilon_{f,1}(E) = \epsilon_{\infty} + \frac{2}{\pi} \int_{E_g}^{\infty} \frac{\xi \epsilon_{f,2}(\xi)}{\xi^2 - E^2} d\xi, \quad \epsilon_{f,2}(E) = \begin{cases} \frac{A_m C E_0 (E - E_g)^2}{(E^2 - E_g^2)^2 + C^2 E^2} \frac{1}{E}, & (E > E_g) \\ 0, & (E \leq E_g) \end{cases}$$

☞ The reference value of the refractive index of the thin film is fixed as a result calculated using the values of the parameters of the Tauc-Lorentz dispersion function below obtained from the silicon nitride thin film thickness certification standard(level of confidence: 68 %, coverage factor: $\kappa=1$).

- $\epsilon_{\infty} = \underline{1.183 \pm 3.175}$
- $A_m = \underline{(64.46 \pm 92.42) \text{ eV}}$
- $C = \underline{(3.245 \pm 4.205) \text{ eV}}$
- $E_0 = \underline{(9.485 \pm 4.639) \text{ eV}}$
- $E_g = \underline{(3.279 \pm 0.407) \text{ eV}}$

☞ The attached certified data were used as fixed input data for the complex refractive indices ($\tilde{N}_s = n_s - ik_s$) of the silicon substrate layer in the analysis model(level of confidence: 68 %, coverage factor: $\kappa=1$).