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Determination of refractive index dispersion and thickness of thin antireflection films TiO_2 and Si_3N_4 on surfaces of silicon photoelectric converters

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Abstract. Offered in this work is the method to determine the thickness and refractive index dispersion of thin antireflection films on absorbing substrates by using a spectral dependence of reflectivity at normal light incidence. The method has been applied to determine the above characteristics of thin antireflection films TiO_2 and Si_3N_4 on surfaces of silicon photoelectric converters. The films were prepared by chemical sedimentation. The obtained experimental data have been treated using a computer program to deduce dispersion curves and thickness values. The results have been interpreted.

Keywords: thin film, refractive index, antireflection film, spectral dependence, photoelectric converter.

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1. Introduction

Silicon photoelectric converters correspond to plates of rather large area covered with antireflection films often prepared by chemical sedimentation. Using the latter method, it is necessary to simultaneously and promptly determine the refractive index dispersion and thickness of these films in various places of the plate. Usually, the dispersion of refractive index $n(\lambda)$ (λ is a light wavelength) and thickness of a film d are measured by either reflectometric or ellipsometric methods by using Airy formulas [1]. Thus, as we have two unknown values n and d it is necessary to have two Airy equations. It is experimentally performed via measurements of reflectivity or ellipsometric parameters at two angles of light incidence. The latter considerably increases the time of measurements. To use the reflectivity R at normal light incidence would be the most effective from the viewpoint of decreasing the time of measuring, but in this case we have only one equation with two unknown values.

In this work, we have applied simple and express methods to determine $n(\lambda)$ and d by measuring the dispersion of reflectivity $R(\lambda)$ at normal light incidence.

2. Experiment

The silicon surface relief in the photoelectric converter represents tetrahedral isosceles pyramidal structure which in a slit is shown in Fig. 1. From top it is coated by TiO_2 or Si_3N_4 film which is considered uniformly distributed over the surface of pyramid since the thickness of the film d is much less than the height of the pyramid h (d is of the order of 100 nm and h − 5000 nm). The cross-section vertex angle makes 70°. TiO_2 and Si_3N_4 films were deposited on silicon plates by chemical sedimentation.

In Fig. 1, I_0 is the intensity of incident light, and I – intensity of reflected light. At normal incidence of light on a plate, the angle of incidence on the first facet of the pyramid $\varphi_1 = 55°$, and on the other one $\varphi_2 = 15°$ (Fig. 1). At each from two reflections from faces of the pyramid shown in Fig. 1, it is necessary to consider multi-reflections in the surface film, which are determined by Airy formula for the reflected wave in a thin film.

If the first medium (air) is marked by the index 1, a thin film – by the index 2, and silicon – by the index 3, reflection amplitude coefficients at a wavelength λ_1 for *p*- and *s*-components will be determined by the formula [1]:

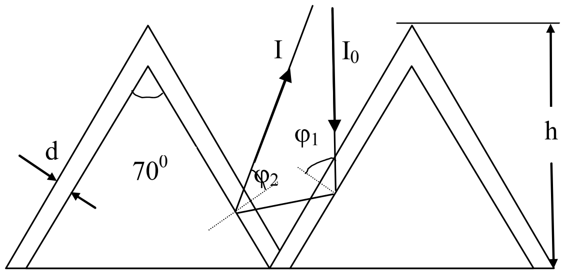

Fig. 1. Scheme of photoelectric converter surface with tetrahedral isosceles pyramidal structure.

$$r^{p,s} = \frac{r_{12}^{p,s} + r_{23}^{p,s} e^{2i\beta}}{1 + r_{12}^{p,s} \cdot r_{23}^{p,s} e^{2i\beta}} . \quad (1)$$

Where $r_{12}^{p,s}$ and $r_{23}^{p,s}$ are Fresnel reflection amplitude coefficients on interfaces 1-2 and 2-3 for *p*- and *s*-components; $\beta = \frac{2\pi}{\lambda_1} n_2 d \cos\chi$, where n_2 is the refractive index of the film, χ − angle of light refraction in the film. Applying the formula (1) for two reflections shown in Fig. 1, we will obtain four values of reflection amplitude coefficients from first and second faces r_1^p, r_1^s, r_2^p, r_2^s.

Energy reflective coefficients from the first and second faces according to [1] are calculated as

$$R_1 = \frac{\left|r_1^p\right|^2 + \left|r_1^s\right|^2}{2}; \quad R_2 = \frac{\left|r_2^p\right|^2 + \left|r_2^s\right|^2}{2} . \quad (2)$$

Resulting energy reflective coefficients from the system shown in Fig. 1 for the wavelength λ_1 are as follows:

$$R_{\lambda_1} = \frac{I}{I_0} = R_1 \cdot R_2 . \quad (3)$$

For the second wavelength λ_2, we will obtain similar correlations for R_{λ_2}. But measuring these two coefficients R_{λ_1} and R_{λ_2} experimentally, we won't be able, having solved the transcendental equations given above, to determine three unknown values, namely: $n_2(\lambda_1)$, $n_2(\lambda_2)$ and d. Therefore, we offer the following method to determine the refractive index dispersion for the surface antireflection film and its thickness.

We measure a spectral dependence of reflectivity $R(\lambda)$. We separate the interval of the used wavelengths into small intervals $\Delta\lambda = \lambda_1 - \lambda_2$, and for each interval we consider that the refractive index in this interval is constant. For a normal dispersion it is admissible. Then, for two equations defining R_{λ_1} and R_{λ_2}, we have only two unknown values n and d. With known numerical methods (for example Newton's method) these equations can be solved by means of computer programs. Thus, for each interval $\Delta\lambda$ the n mean value will be obtained for the wavelength λ_3 defined below:

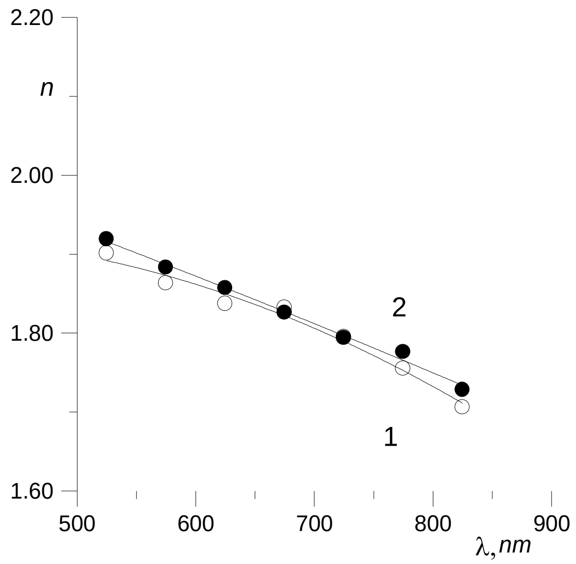

Fig. 2. Spectral dependences of the refractive index: 1 – TiO_2, 2 – Si_3N_4.

$$\lambda_3 = \frac{\lambda_1 + \lambda_2}{2} .$$

In the part of anomalous dispersion, this method requires very small values of the interval $\Delta\lambda$, and its accuracy decreases.

3. Results and discussion

Spectral dependences of reflectivity in a visible and near infrared ranges of spectrum for the silicon photoelectric converters coated with TiO_2 and Si_3N_4 films have been measured using Fourier spectrometer Vertex-70 with a reflecting device. Data of measurements were calculated by means of the program "MathCAD" and formulas (1)-(3), as it is described in Section 2. Optical constants of silicon were taken from [2].

The obtained results for the refractive index dispersion are given in Fig. 2. The curve 1 is for the film TiO_2, and curve 2 for the film Si_3N_4. The mean thickness value for a film makes 116 nm for TiO_2 and 113 nm for Si_3N_4. First of all, it is necessary to note that obtained values of the refractive indexes are a bit lower than the literature data, namely: $n = 2.3$ for TiO_2 films produced by vacuum sputtering according to [3] and $n = 2.1$ for bulk Si_3N_4 according to [4]. But, as shown in [4] impurities of oxygen in bulk samples of Si_3N_4 reduce the refractive index to the values 1.7−1.8. During hot pressing, replacement of nitrogen by oxygen leads to formation of silicon oxy-nitride Si_3N_2O.

Similar processes can occur at chemical sedimentation of Si_3N_4 and TiO_2 films that can lead to a decrease in the refractive index of films. It is known [4, 5] that for bulk samples of Si_3N_4 and TiO_2 the dispersion in the range of the spectrum chosen by us is normal, which is confirmed by curves 1 and 2 in Fig. 2.

4. Conclusion

The results obtained for the dispersion of refractive index of TiO_2 and Si_3N_4 films produced using chemical sedimentation are valid and show that the offered method to calculate the dispersion of refractive index for thin antireflection films and their thickness can be applied within the range of a normal dispersion of refractive index in the studied films. It can be used for express determination of a dispersion of the refractive index and thickness of antireflection films deposited on photoelectric silicon converters used for measuring the spectral dependence of reflectivity at normal light incidence on their surface.

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