АНАЛІТИЧНЕ ТА ЕКОЛОГІЧНЕ ПРИЛАДОБУДУВАННЯ

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ANALYSIS OF THE STRUCTURE OF INTERFERENCE COATINGS FOR THE OPTIMIZATION OF THE PARAMETERS OF NARROWBAND OPTICAL FILTERS

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To monitor the parameters of semiconductor layers deposited from solid solutions of A3B5 compounds during the epitaxy, optical control methods are used. The choice of optical monitoring methods is determined by the reactor design, which requires non-contact, fast, and precise measuring of wafer surface parameters.

During the growth of epitaxial layers, the deposition of semiconductor compounds causes changes in the optical parameters of the wafer surface. To ensure precise measurements, it is essential to monitor these parameters within a narrow spectral range. In electro-optical monitoring systems, narrowband interference filters are used to select the desired spectrum. However, this type of filters is sensitive to several factors, such as environmental conditions, aging of the coating, and the angle of incidence. As a result, the manufacturing of narrowband optical filters with stable and precisely controlled optical characteristics presents a complex challenge.

This article analyzes the impact of various factors on the optical characteristics of interference coatings. Quantitative analysis of these shows that shift of the selected spectral band with central wavelength λmax can approach or even exceed the full width at half maximum (FWHM). These changes in the optical characteristics of narrowband filters lead to a decrease in the accuracy required for optical monitoring during epitaxial processes, which leads to inaccuracies in measurements.

The results of this analysis will guide the optimization of thin-film structures used in narrowband optical filters. The study of the shift in the selected band also enables, within certain limits, controlled changes to λmax or the compensation of its shift its shift during regular factor variations. Ultimately, it enables to take these changes into account when designing electro-optical systems for monitoring the epitaxial growth of semiconductor heterostructures, which increases the accuracy and stability of optical measurements in the required accuracy range.

Keywords: *interference coatings; narrowband filters; optical properties; stability of characteristics; MOCVD.*

Introduction

Currently, quantum electronics and related emerging fields have necessitated the development of interference coatings with several new characteristics. Thus, one of the most complex problems related to the development of thin-film systems, in particular narrowband filters with strictly stabilized and controlled optical characteristics, has arisen. This demand has driven researches into the effects of various factors (such as time, environmental conditions, temperature, etc.) on the optical parameters of interference coatings. In this context, narrow-band filters receive special attention, as the spectral band shift is comparable to or even exceeds the full width at half maximum (FWHM).

The optoelectronic temperature monitor system for vapour-phase epitaxy technology consists of a pyrometer for measuring the flow of thermal radiation from the wafer and a reflectometer for determining the true value of the optical parameters of its surface. The system includes two photodetectors, an infrared radiation source, narrowband optical filters, a system of mirrors, and beam splitters. Silicon photodiodes with stabilized characteristics in the measurement spectral range are used as photodetectors [1]. The main photodiode measures the thermal radiation from the heated wafer in the reactor, while the feedback photodiode stabilizes the infrared radiation source, which is a LED with stabilized characteristics with an optical collimation scheme. The developed collimation system, with an aperture diameter of 120 μm, has an angular divergence of up to 7 arcseconds, allowing the use of the developed radiation source in pyrometric systems with various focal lengths ranging from 10 to 50 cm for different types of growth reactors [2].

For optical temperature control systems in the process of metal-organic chemical vapor deposition (MOCVD), it is critically important to adhere to specific conditions and temperature regimes. The required accuracy for determining the surface temperature must be within ± 0.4 °C [3]. For example, typical temperature ranges for the growth of InP compounds are considered to be between 600 and 650 °C, for GaAs growth between 700 and 800 °C, and for GaN compound growth, 1000 °C or higher.

The amount of thermal radiation reaching the sensitive area of the photodetector is proportional to the amount of the optical signal, which passes through the optical unit of the monitoring system, consisting of narrowband filters, and is also dependent on the spectral sensitivity of the silicon photodetector. Therefore, a trade-off exists between maintaining sufficient optical signal strength for its processing and keeping the bandwidth of the optical filter as narrow as possible to minimize measurement errors because of the real measurement conditions. It is impossible to measure the reflected radiation from the wafer *R* by the reflectometer unit and the thermal radiation *L* by the pyrometer unit under the identical conditions. In other words, it is impossible to measure the signal values at the same wavelength, angle of incidence and polarization for further calculation of the true temperature. Instead, measurements are made in a certain range of wavelengths, angles of incidence and states of polarization of light. The measured signal of the pyrometer s and the reflectometer r are determined as:

$$\begin{aligned} s &= \int\limits_{\Delta\lambda,\Delta\theta,\Delta\sigma} f(\lambda,\theta,\sigma)L(\lambda,\theta,\sigma,T)\mathrm{d}\lambda\mathrm{d}\theta\mathrm{d}\sigma, \\ r &= \int\limits_{\Delta\lambda,\Delta\theta,\Delta\sigma} g(\lambda,\theta,\sigma)R(\lambda,\theta,\sigma,T)\mathrm{d}\lambda\mathrm{d}\theta\mathrm{d}\sigma. \end{aligned} \tag{1}$$

Where, Δλ – the wavelength range, Δθ – the range of incidence angles, Δσ – the range of polarization states, f and g – the response functions of the pyrometer and reflectometer units.

Analyzing the dependence of the accuracy in determining the temperature of a blackbody using the method of effective wavelength approximation, two types of filters were considered: with a Gaussian and a Square-wave filter response. The filter with a rectangular passband demonstrates significantly better performance, as the effective wavelength exhibits a more linear dependence on temperature compared to the Gaussian filter. Additionally, the range covered by the effective wavelength is nearly an order of magnitude smaller. The dependence is linear, and therefore for measurements of objects whose emissivity ε is constant throughout the entire spectral range (black and grey bodies), it can be used as a correction factor allowing the use of a wider spectrum band with the sufficient optical signal level and required accuracy. However, in the process of vapour-phase epitaxy, the spectral emissivity ε of the wafer surface is spectral dependent, which is associated with the deposition of thin epitaxial layers. Thus, the application of the effective wavelength approximation method becomes impossible due to the complexity of processing of obtained data. Therefore, to achieve the required accuracy, it is necessary to use a narrow spectral range. It was established that for a wavelength λ_{max} of 930 nm and a transmittance T of no less than 80%, the optimal filter bandwidth Δλ is 10 nm [4].

Problem statement

In narrowband optical filters, the influence of factors such as changing environmental conditions, coating aging, and incidence angle cause a shift in the central wavelength λmax of the selected spectral band comparable to or greater than the full width at half maximum (FWHM), causing the challenges for precise optical measurements. This study is devoted to the analysis of thin-film interference coatings with the aim of optimizing the design of narrowband optical filters for their application in optical systems used to monitor the growth parameters of epitaxial layers. The primary objective of the paper is to assess the impact of external factors on the characteristics of optical filters, which will enable the consideration of their shifts under regular changes in external conditions and provide the ability of their stabilization and adjustment within controlled limits.

Theory the Optical Properties of Thin Films and Methods for their Calculating

Mathematically, thin films are described as infinitely large, flat, parallel layers with thickness comparable to the wavelength of light. These layers are characterized by refractive indices and, for absorbing layers, absorption coefficients. Multilayer thin-film systems are composed of a finite number of these layers, each with distinct optical properties.

The primary quantities in thin film optics are the electric field intensity vector $E(z)$ and the magnetic field intensity vector $H(z)$. These are determined from Maxwell's equations under certain boundary and initial conditions. So, there are two main tasks in thin-film optics. The first task is to calculate the intensities of reflected, transmitted, and absorbed light, and to determine the phase change at different wavelengths, angles of incidence, and polarizations for a given multilayer system with known thicknesses and optical constants of the layers.

The second task requires selecting a multilayer system from available film materials with known optical characteristics to achieve specified values of reflection, transmission, absorption, and phase change in a certain range of wavelengths and angles of incidence using different calculation methods [5, 6].

Although these problems have been the subject of much work in recent years, there is no single solution method that can be applied to all problems. The most widely used and convenient method is the matrix representation, where the *i*-th layer with optical thickness d_i and index of refraction n_i can be represented as:

$$M_i = \begin{bmatrix} \cos\varphi_i & (\mathrm{i}/\eta_i)\sin\varphi_i \\ \mathrm{i}\eta_i \sin\varphi_i & \cos\varphi_i \end{bmatrix}, \tag{1}$$

where, pseudoindex of the *i*-th layer η_i is:

$$\eta_i = \begin{cases} n_i \cos\theta_i & \text{s polarization} \\ n_i / \cos\theta_i & \text{p polarization} \end{cases}, \qquad (2)$$

and the phase shift of the phase shift of a lightwave of length λ which is incident at an angle θ:

$$\varphi_i = \frac{2\pi}{\lambda} n_i d_i \cos\theta_i . \qquad (3)$$

The characteristic matrix that describes the entire multi-layer with q number of layers structure is described as follows:

$$M = \prod_{i=q}^{1} M_i = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}. \qquad (4)$$

Based on this, the reflection and transmission amplitudes can be found as:

$$r = \frac{\eta_0 m_{11} - \eta_1 m_{22} + \eta_0 \eta_1 m_{12} - m_{21}}{\eta_0 m_{11} + \eta_1 m_{22} + \eta_0 \eta_1 m_{12} + m_{21}}, \qquad (5)$$

$$t = \frac{2\eta_0}{\eta_0 m_{11} + \eta_1 m_{22} + \eta_0 \eta_1 m_{12} + m_{21}}, \qquad (6)$$

where η_0 – the pseudoindex of incidence media, η_1 – the pseudoindex of exit media.

The transmittance and reflectance values can be found as:

$$R = |r|^2 , \qquad (7)$$

$$T = \frac{\operatorname{Re} n_1}{\operatorname{Re} n_0} |t|^2 . \qquad (8)$$

Dependency of the Filter Characteristics on the Change in Layers Thickness

The influence of temperature, angle of incidence and some other factors on the position of the maximum transmission λ_{max} of the interference filter is determined by a single formula. In the case of a symmetric filter and a light flux falling on the filter from the side of the medium with number m+1, it is assumed that the main influence on the position of the center is exerted by a change in the effective optical thicknesses of the filter layers:

$$h_k = n_k d_k \cos\varphi_k \ (\text{k = 1, 2 ... m}). \qquad (9)$$

Where, φ_k – the angle of refraction of the beam in the layer with the number k.

The indices of the layers n_k depend on the temperature and wavelength, the geometric thicknesses d_k depend on the temperature, the values of cos φ_k depend on the angle of incidence of the φ_{m+1} flow onto the filter.

In the absence of absorption, the deviation Δλ from the given value λ_0 is related with a change in the optical thicknesses of the layers as:

$$\frac{\Delta\lambda}{\lambda_0} = \frac{1}{\pi} \sum_{k=1}^{m} A_k \Delta\alpha_k , \qquad (10)$$

$$\lambda_{max} = \lambda_0 + \Delta\lambda. \qquad (11)$$

Where, α_k – coefficient of absorption, A_k – coefficient that depends on the properties of the k-th layer of the interference filter.

Let's consider a 23-layer filter, which is made on the basis of alternating layers of Si/SiO with the HLHL4LHLHLHLHLHL4LHLHLH stack formula, where H is the Si layer, B is the SiO layer. The design is a quarter-wave stack with an optical layer thickness of $\lambda_{ref}/4$.

Taking into account the spectral dependence of the refractive indices of the layers [7, 8, 9, 10, 11], at a wavelength of λ_{ref} = 930 nm, the refractive index profile and thickness of layers are shown in Figure 1.

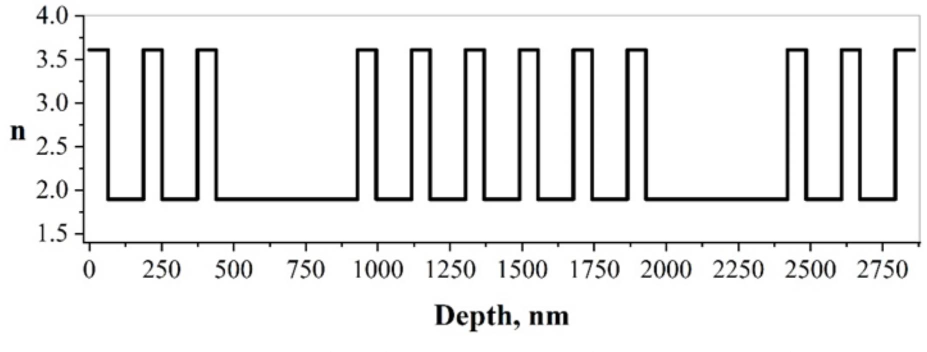

Fig. 1. Index profile of the analyzed thin-film structure at reference wavelength

Using the abovementioned theory, the transmission of a narrow-band filter was calculated, the obtained characteristic is shown in Figure 2. To smooth out the peak of the transmission characteristic during the manufacture of the filter, a layer with an intermediate refractive index value was added, which made it possible to obtain a contrast narrow-band filter. The transmission measured with the spectrophotometer is presented in Figure 2.

The measured characteristic was approximated using the needle method [5]. To assess the impact of changing the layer thickness, calculations with a 2 %-layer thickness variation were made, the analysis is presented in Figure 3.

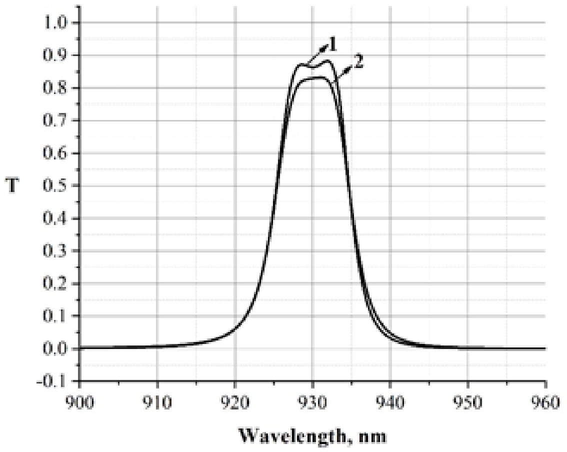

Fig. 2. Transmittance of the calculated narrow-band filter: 1 − calculated; 2 −measured

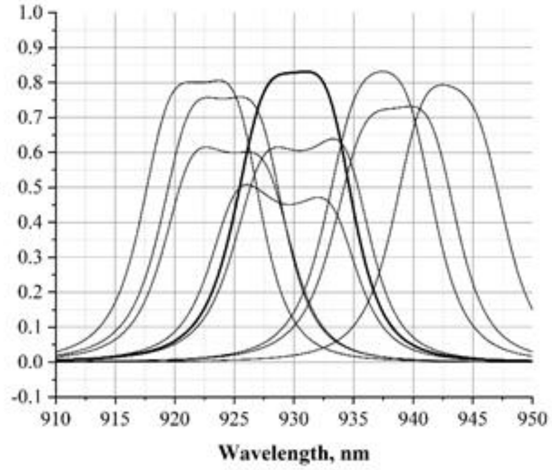

Fig. 3. Calculation of 2 % optical thickness variations with uniform distribution

As can be seen from the simulation, a change in the optical parameters of the layers, which is due to external factors, affects the optical thickness of the thin layers and, as a consequence, the position of the central wave λ_0, the transmission width at half maximum FWHM and the symmetry of the characteristic in different ways. As a consequence, for a controlled change in the characteristic shift, further study of each factor separately is needed.

Dependency of the Filter Characteristics on Angle of Incidence and Temperature

When tilting the filter, the characteristics shift to the short-wave region. The dependence of the wavelength λ on the angle of incidence is also conveniently used for accurately matching the position of λ with the required value. However, it should be borne in mind that tilting the filter is advisable until there is a noticeable deterioration in the characteristics, i.e. an increase in the half-width and a decrease in the transmission T. The rate of wavelength shift is determined by the effective refractive index n_e, which is intermediate between materials with high and low refractive indices of a thin-film structure and can be represented as:

$$n_e = n_L \left[\frac{m-(m-1)(n_L/n_H)}{m-m(n_L/n_H)+(n_L/n_H)^2} \right]^{1/2},$$

$$n_e = n_H \left[\frac{m-(m-1)(n_L/n_H)}{(m-1)-(m-1)(n_L/n_H)+(n_H/n_L)} \right]^{1/2}.$$

At oblique incidence, the refraction for s-polarization ns = n cosθ, and the refraction for p-polarization np = n / cosθ, where n is the refractive index at normal incidence. Thus, the central wavelengths of s-polarized and p-polarized light will separate as the angle of incidence increases. The temperature dependence of the refractive indices of the filter materials exhibits a linear behavior [12]. Therefore, the shift in the central wavelength is reversible upon cooling and predictable due to the linear variation of the refractive indices of the materials used in the filter's construction. In narrowband filters, significant shifts can be induced by thermal radiation incident on the filter. Additionally, a sharp temperature increase during the thermal treatment process may cause film delamination due to stress buildup within the layers. Therefore, determining the optimal temperature regime is essential to ensure reproducible characteristics and reliable long-term operation of the filter.

The change in the transmission characteristic of the above optical filter was measured. To implement it, a thin-film coating was deposited onto a glass substrate, which was glued to an 850 nm longpass filter. The results are shown in Figure 4.

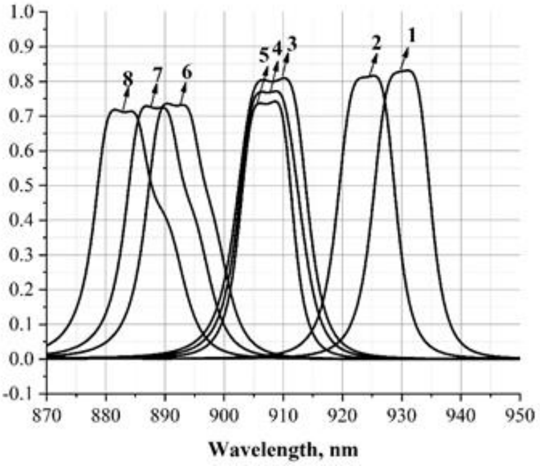

Fig. 4. Angular dependence of the transmission of the calculated narrow-band filter
1 − 0°; 2 − 15°; 3 − 30° p-pol; 4 − 40°; 5 − 30° s-pol; 6 − 40°; 7 − 42°; 8 − 45°

From the analysis of experimental data it follows that when a parallel beam falls, narrow-band filters are advisable to use at angles of incidence less than 10°, since in this range of angles the width and transmission change insignificantly and there is practically no splitting of the spectral transmission curve into 2 components polarized in mutually perpendicular planes (Figure 4). This effect is usually observed at angles of incidence greater than 25°.

This means that at given angles the light beam is split into two beams with different polarization directions, which can affect the operation of the optical system. The spectral transmission curve T, which was a single function at small angles, begins to split into two different curves for each of the polarized light components. As a result, each polarized component will have its own transmission characteristic, i.e. the transmission for a light beam polarized in one plane will differ from the transmission for light polarized in another plane. At large angles of incidence, the light passing through the filter will be polarization dependent. This can lead to a change in the overall filtration characteristic and a decrease in the filter efficiency if the system does not take polarization effects into account. For a given angle of incidence, splitting can be avoided by design optimization, such as by changing the thickness of the separation layer of the interference filter or by matching the effective optical thicknesses of the layers along the beam path.

Conclusions

In this study, the structure of interference coatings was analyzed to optimize the parameters of narrow-band optical filters.

Additionally, the characteristics of the optoelectronic system of the pyrometer-reflectometer for monitoring the epitaxy process, which determine the necessary requirements for filter parameters, were examined.

A narrow-band optical filter was designed using numerical calculation methods. The analysis of theoretical and experimental data of manufactured filter enabled a quantitative investigation of the factors affecting the performance of narrow-band optical filters.

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АНАЛІЗ СТРУКТУРИ ІНТЕРФЕРЕНЦІЙНИХ ПОКРИТТІВ ДЛЯ ОПТИМІЗАЦІЇ ПАРАМЕТРІВ ВУЗЬКОСМУГОВИХ ОПТИЧНИХ ФІЛЬТРІВ

Для контролю параметрів напівпровідникових шарів, отриманих із твердих розчинів сполук A3B5 під час епітаксії, використовуються оптичні методи. Вибір методів оптичного моніторингу визначається конструкцією реактора, яка вимагає безконтактних, швидких і точних методів вимірювання параметрів поверхні підкладок.

Під час росту епітаксійних шарів осадження напівпровідникових сполук викликає зміну оптичних параметрів поверхні пластини. Для забезпечення точних вимірювань необхідний контроль даних параметрів у вузькому спектральному діапазоні. В електрооптичних системах моніторингу для виділення необхідного спектру використовуються вузькосмугові інтерференційні фільтри. Однак, цей тип фільтрів чутливий до ряду факторів, таких як умови навколишнього середовища, старіння покриття та кут падіння. Як результат, виготовлення вузькосмугових оптичних фільтрів зі стабільними та точно контрольованими оптичними характеристиками представляє комплексну задачу.

У статті проаналізовано вплив різних факторів на оптичні характеристики інтерференційних покриттів. Кількісний аналіз показує, що зсув виділеної смуги спектру з центральною довжиною хвилі λ_{max} може наближатися до або навіть перевищувати повну ширину на половині максимуму (FWHM). Ці зміни в оптичних характеристиках вузькосмугових фільтрів призводять до зниження точності вимірювань параметрів епітаксійних шарів.

Результати цього аналізу сприятимуть оптимізації конструкції тонкоплівкових структур, що використовуються в вузькосмугових оптичних фільтрах. Дослідження зміщення виділеної смуги також дозволяє здійснювати у деяких межах контрольовану зміну λ_{max} або враховувати її зміщення при регулярній зміні факторів. У кінцевому підсумку, це дозволяє врахувати ці зміни під час проектування електрооптичних систем для моніторингу епітаксійного росту напівпровідникових гетероструктур, що підвищує точність і стабільність оптичних вимірювань у необхідному діапазоні точності.

Ключові слова: інтерференційні покриття; вузькосмугові фільтри; оптичні властивості; стабільність характеристик, ГФЕ МОС.

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