АНАЛІТИЧНЕ ТА ЕКОЛОГІЧНЕ ПРИЛАДОБУДУВАННЯ

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SPECIFICS OF DESIGNING AN INFRARED PYROMETER-REFLECTOMETER FOR SEMICONDUCTOR HETEROSTRUCTURE FABRICATION

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There are general technical requirements for all types of reactors for chemical vapour deposition technology using AIII- BV metalorganic compounds. Among them, it is worth highlighting the large temperature gradients that cause the origin of convection loops, which in turn, taking into account the high speed of the gas flow, lead to turbulence in the reactor instead of the expected laminar flow. It is also important to take into account the change in parameters of the wafer surface during the growth process and the need for signal separation between the useful signal from the wafer surface and the background signal from the wafer carrier, which rotates at fixed speed for uniform deposition of compounds.

To obtain high-quality heterostructures with reproducible parameters, it is important to have a system of precise temperature control on the wafer surface directly in the deposition area, since the deposition process for many complex semiconductor devices (for example, laser diodes, LEDs, photodiodes, transistors on heterojunctions) is very sensitive to temperature changes. The method of optical pyrometry is a non-contact method that allows to precisely determine the temperature of the wafer surface and meets the technical requirements of CVD epitaxy growth reactors.

This article is devoted to the analysis of the features of the development of optoelectronic systems for precise temperature measurement during epitaxial growth in order to determine the criteria for the selection or development of components of the optoelectronic system of the pyrometer-reflectometer. The main physical processes, electro-optical characteristics of Si photodiode, AlGaAs/GaAs LED and parameters of bandpass interference filters were investigated.

Based on the analysis of the obtained research and measurement results, scientific recommendations have been developed. The recommendations aimed at the selection and optimization of the parameters of the components of the pyrometer-reflectometer (photodetectors, light emitting diodes, optical filters) in order to improve the accuracy and temperature stability of measurements in the pyrometer's operation conditions, which take into account the compensation of emissivity change from the surface of the wafer.

Keywords: *AIII-BV semiconductors; metalorganic chemical vapour deposition; MOCVD; photodiode; light emitting diode; pyrometry with emissivity compensation; optoelectronic systems for monitoring parameters; optical filter.*

Introduction

Currently, the main method of obtaining semiconductor heterostructures based on AIII-BV solid solutions for micro-optoelectronic devices is the method of metalorganic chemical vapour deposition (MOCVD). This method allows for the production of high-quality semiconductor structures with a minimal number of defects in the crystal lattice.

During epitaxial layer growth, one of the important parameters is the wafer temperature. This parameter is particularly crucial for obtaining quantum-sized structures, active layers of lasers, and LEDs [1]. For example, in emitting semiconductor devices, a change in the temperature of the wafer from that specified in the technological recipe, or temperature non-uniformity across the wafer surface leads to variations in one of the main parameters – the wavelength of radiation. Therefore, precise temperature control during the deposition of epitaxial layers is a critical aspect. To obtain layers with the necessary parameters, during the epitaxy process, it is necessary to maintain the temperature with an accuracy of ±0.4 °C [2].

The technology of chemical vapor deposition (CVD) involves the use of highly reactive reagents at high temperatures. To ensure maximum purity, there should be no impurities in the reactor environment that can cause unwanted chemical reactions. Epitaxy occurs by depositing reagents on the surface of a semiconductor wafer. Epitaxy occurs by depositing reagents onto the surface of the semiconductor wafer. To ensure a laminar flow during deposition, the wafer, which is placed on a graphite carrier, rotates at a fixed speed that depends on the design and parameters of the reactor.

Optical methods, particularly optical pyrometry, are used for temperature control. This method allows for non-contact temperature measurement of the wafer surface inside the reactor. However, during the heteroepitaxy process, the optical properties of the wafer surface change, so the temperature control system must take these changes into account. To solve this issue, a method called emissivity-compensated pyrometry is employed. This method consists in measuring not only the thermal radiation of the plate, but also in the additional measurement of the reflectivity of its surface using a reflectometer to compensate for changes in the optical parameters of the wafer surface and further precise determination of the real temperature.

Depending on the tasks and the spectral range of measurement, silicon photodiodes [3], GaAs photodetectors [4], position-sensitive photodetectors, including matrices of photosensitive elements [5] are used in radiation-compensated pyrometers-reflectometers. The use of position-sensitive photodetectors allows to control the change in the curvature of the plate surface during epitaxy, using optical deflectometry methods.

Problem statement

The research task consists in a detailed analysis of the method of registration and formation of an optical signal in a pyrometer-reflectometer, determination of the optimal spectral range, research of the characteristics of detectors and IR range emitters. The purpose of the article is to determine the main technical criteria for the selection or development of optoelectronic elements for a precision substrate temperature control system during the production of semiconductor heterostructures based on AIII-B5 solid solutions for micro-optoelectronics devices fabrication.

Functional scheme of the pyrometer-reflectometer optical unit

To ensure the laminar flow of the depositing reagents, the wafer carrier rotates at a fixed speed determined by the design and parameters of the reactor. Considering that physical sensors have inertia and the impossibility of directly measuring the temperature of the wafer surface, as well as separating the signal from the wafer surface and the wafer carrier, the use of physical sensors such as thermocouples is insufficient. As a result, to achieve the desired accuracy, the temperature control system requires a non-contact and low-inertia optical method that considers for the dynamic changes in the optical parameters of the wafer surface [6].

To account for the change in the emissivity of the wafer surface ε, an optical pyrometry method is used, which involves additional measurement of the signal reflected from the wafer surface using a reflectometer. The substrate's reflectance coefficient R is measured at the same wavelength at which the thermal radiation measurement is conducted.

By applying Kirchhoff's law for optically opaque bodies $\varepsilon = 1 - R$, the emissivity of the wafer surface ε can be determined based on the measured reflectance R. This allows for continuous correction of the measured pyrometric signal, taking into account changes in the wafer surface`s emissivity coefficient. Thus, accurate and continuous real-time measurement of the wafer`s temperature is ensured during the epitaxy process. This method avoids distortions in measurements and provides high accuracy in determining the temperature, which is critically important for obtaining epitaxial layers with high crystalline perfection. The functional diagram of the optical unit of the pyrometer-reflectometer for detecting the pyrometric signal from the reactor is shown in Figure 1.

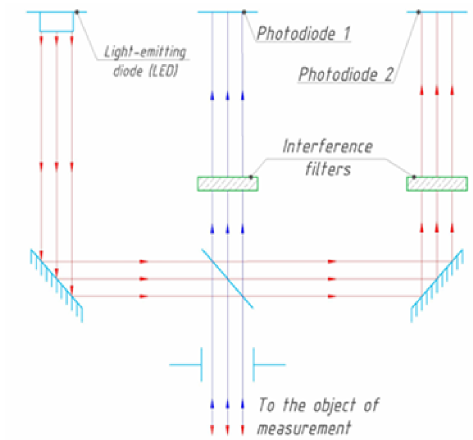

Fig. 1. Functional scheme of the pyrometer-reflectometer`s optical unit

The pyrometer consists of a primary photodiode (photodiode 1), which simultaneously serves as the detector for both the thermal radiation from the wafer and the modulated optical signal reflected from the wafer surface. This signal is generated through the pulsed modulation of the current of an LED, which acts as the optical radiation source. The modulation frequency is determined by the specific design of the reactor: the rotation frequency of the wafer carrier in the reactor, the size of the wafer, the response speed of the optical signal registration system, the required number of measurements on the wafer, and the range of measurement temperatures [7].

Based on the results of analytical calculations and conducted experiments, it can be stated that for vertical type reactors with a turbo-disk system, characterized by a wafer carrier rotation frequency of up to 1000 revolutions per minute, in the temperature range from 450 to 1200 °C, using a Si planar photodiode as the detector, the LED modulation frequency should be from 10 to 30 kHz. The range of the LED current modulation depth is determined by the power of the optical signal reflected from the wafer`s surface, which in turn should be comparable to the power of the optical radiation from the heated wafer in the specified spectral range. Thus, the photodetector output forms two electrical signals: a constant one, whose value is proportional to the wafer temperature, and a variable one, reflected from the wafer surface and modulated in amplitude. The maximum value of the reflected signal depends on the optical properties and the thickness of the deposited epitaxial layer. Further processing of the analog signal and mathematical analysis of these signal values provide the actual temperature at each measurement point on the substrate in real-time. The oscilloscope trace of the electrical pulses from photodetector 2 is shown in Figure 2.

Fig. 2. Oscillogram of photodetector electrical pulses

When designing the amplification unit for the electrical signal from photodetector 2 to ensure the required measurement accuracy across the entire temperature range, it is necessary to optimally match the calculated output voltage values from the photodetector preamplifier with the dynamic range of the main amplifier and ADC. Additionally, the capability to automatically adjust the gain of the main amplifier and accordingly the depth of the LED current modulation based on the measured temperature value should be considered. The overall view of the photodetector with the amplifier board is shown in Figure 3.

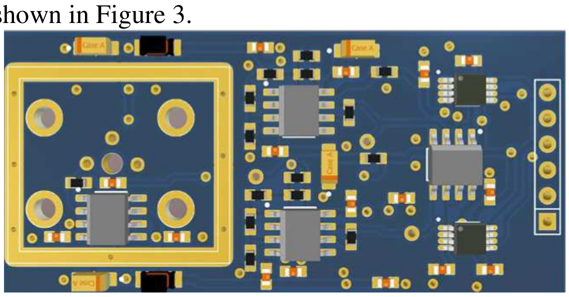

Fig. 3. Photodetector amplifier PCB

When designing the pyrometer-reflectometer, special attention must be paid to stabilizing the parameters of the active electro-optical components of the device, namely the photodetector and the LED. It is crucial to minimize the influence of external factors, such as the impact of ambient temperature on the measured optical signal value.

To stabilize the optical power of the IR LED in the device, an optical feedback channel has been created: a portion of the optical signal, determined by the parameters of the optical splitter, is directed onto photodiode 2 via a system of mirrors. This photodiode measures the amplitude of each optical pulse directed at the wafer and serves as a control signal for the LED current control circuit.

By employing narrowband interference optical filters, power stabilization occurs precisely in the spectral range where photodetector 1 operates. The accuracy of the wafer temperature determination depends on the filter's bandwidth. According to the calculations, the optimal bandwidth is between 10 and 14 nm [8]. Conversely, if the bandwidth is less than 10 nm, the input optical signal from the wafer is significantly reduced, making it impossible to measure the substrate temperature below 550 °C.

Since the temperature calculation relies on the values of the optical analog signal, which is generated and processed using components of the optoelectronic system, a detailed analysis of these components in the spectral measurement range of 930 nm is necessary. This analysis is crucial for selecting and optimizing the parameters of these components to enhance the accuracy and stability of temperature measurements in pyrometers operating under conditions that consider the emissivity compensation method. In other words, it is essential to minimize the influence of external factors on measurement accuracy.

Selection of the photodetector

In pyrometry systems used for high-precision temperature measurement, a silicon p-n photodiode is used as a key component. The efficiency of this photodiode is determined by several critical parameters: high watt-ampere sensitivity, minimum values of dark current and speed of response. High watt-ampere sensitivity is important to ensure the accuracy of measurements, especially when detecting optical signals of low power [9].

The dark current flowing through the photodiode in the absence of illumination should be minimized to reduce noise and improve measurement accuracy. The low dark current ensures that measurements are more stable and less subject to random fluctuations, which is especially important when measuring weak signals. The dark current in photodiodes is usually proportional to the area of their active zone. This means that as the active zone area increases, the overall dark current also increases. The primary cause of dark current is the thermal generation of electron-hole pairs. Photodiodes with larger active zone areas have more volume where such pairs can be generated, leading to an increase in the overall dark current. In addition to volume dark current, there is also surface dark current, which arises at the p-n junction interface. As the active zone area increases, so does the surface current.

Therefore, when choosing the area of the photodetector for the pyrometer-reflectometer, it is necessary to make the optimal choice between two conflicting factors. On one hand, reducing the area of the photodetector element will lead to a decrease in dark current, an increase in threshold sensitivity, and a reduction in its temperature dependence. This will allow for measuring low wafer temperature values with minimal error over a wider temperature range of the surrounding environment and increase the device's speed, which is particularly important for detecting modulated optical signals. The speed of the photodiode is limited by several factors, including the p-n junction capacitance *C*, the load resistance R, and the carrier lifetime τ. The speed of the photodiode can be approximately estimated by the RC time constant (response time), which is determined as follows: $\tau = RC$.

On the other hand, reducing the area of the photosensitive element may cause the reflected beam from the wafer surface to exceed the boundaries of the photodetector element, especially in devices with a large focal length and when the radius of curvature of the wafer surface changes during epitaxial growth. Based on calculations and experimental results considering the characteristics of the developed optical block of the pyrometer-reflectometer, the optimal size for the Si p-n photodiode ranges from 2.5 to 3 mm.

When selecting the operating wavelength for a Si photodiode, it is necessary to consider a balance between maximum sensitivity and temperature stability of the photodiode's watt-ampere sensitivity in the operating spectral range, which is determined by the change in the width of the silicon bandgap [10]. As the temperature increases, the bandgap width Eg decreases, leading to a shift of maximum sensitivity towards longer wavelengths. The absorption coefficient of silicon α is directly proportional to the bandgap width Eg and inversely proportional to the penetration depth of radiation into the material d. Considering this, it can be said that with increasing temperature of the silicon structure, the penetration depth of the radiation changes, leading to a change in quantum efficiency, which is determined by the depth of the p-n junction and the construction of the photodiode structure.

Accordingly, at high levels of photodiode sensitivity, there is a need to ensure temperature stabilization or to choose a wavelength that provides an optimal balance between sensitivity and stability of characteristics in a wide temperature range. Taking into account the above and based on the analytical model of the watt-ampere sensitivity of the Si photodiode (Fig. 4), the optimal value of the working wavelength is 930 nm, while the temperature drift of the watt-ampere sensitivity is 0.2%/°C [7].

Selection of the IR radiation source

To implement the reflectometer channel, it is necessary to have a highly collimated optical beam in a narrow spectral range with the possibility of fast (10-30 kHz) modulation of the optical power level.

Collimated radiation is obtained using the optical scheme shown in Fig. 5, which ensures the minimum angle of divergence of optical rays. For such an optical system, the most suitable source of optical radiation is an LED.

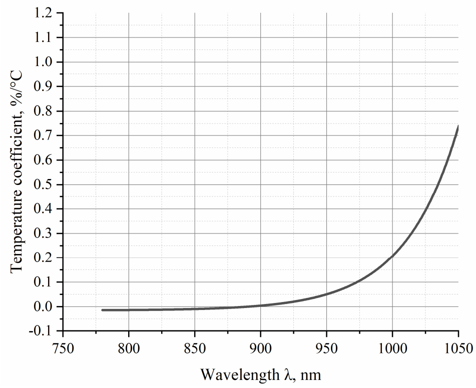

Fig. 4. Experimental dependence of the temperature coefficient of the researched Si photodiodes [7]

Using LEDs allows for forming the emitting area of the required size and shape. For the device the radiation source, an LED with a circular area of 120 µm in diameter was developed. Additionally, LEDs exhibit high quantum efficiency of radiation emission and enable the formation of optical pulses through current modulation across a wide frequency and dynamic range [11].

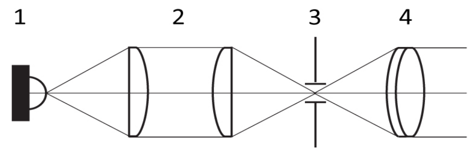

Fig. 5. Radiation collimation optical scheme: 1 – radiation source (LED), 2 – condenser I, 3 – aperture, 4 – condenser II

The developed collimator for the LED, operating at a wavelength of 930 nm with a 120 µm aperture diameter, achieves an angular divergence of optical rays of up to 7 arcseconds. This enables the use of the developed optical radiation source in pyrometric systems with varying focal lengths, ranging from 10 to 50 cm, suitable for different types of growth reactors.

The choice of the wavelength of the LED optical radiation of the reflectometer is determined by the operating wavelength of the pyrometer itself, which is 930 nm. Considering the spectral characteristics, its temperature dependence, the method of optical power stabilization, and the LED power, the central wavelength of the LED emission should be 950 nm. The spectral characteristic of the investigated LED with AlGaAs/GaAs quantum-sized layers and a round light-emitting area with a diameter of 120 µm is shown in Figure 6.

Another important parameter is the power of the emitter. The optical power of the LED in the specified spectral range is determined by the level of power of the pyrometric signal from the heated wafer in the growth reactor and the losses of the optical signal when forming a collimated beam of a certain diameter.

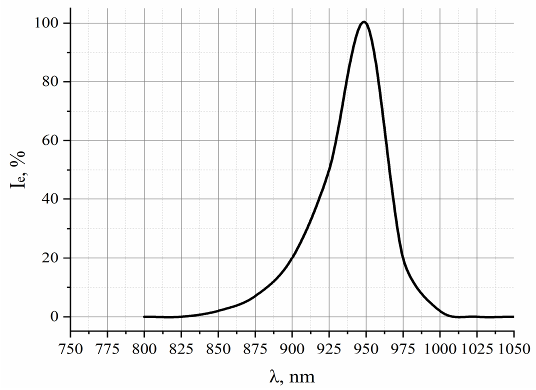

Fig. 6. Spectral radiance of the developed AlGaAs/GaAs LED

These power values should have the same dimension and not go beyond the dynamic range of the pyrometer registration system in the entire temperature range of measurements.

The diameter of the emitter's beam is determined by the size of the circular plane at the focal distance of the photodetector`s 1 objective, formed by a slotted diaphragm located in front of the detector. Considering the design features of the growth reactors, the dimensions of their optical ports, the distance from the reactor surface to the substrate holder, the minimum values of the substrate temperature measurement, the rotation speed, diameter, possible inclination, and change in curvature of the substrates, as well as the aperture of the objective for a vertical reactor with a turbo-disk system, the diameter of the reflectometer beam should range from 4 to 7 mm.

The use of quantum-sized heterostructures in the LED makes it possible to obtain devices with high quantum efficiency, that is, to significantly reduce the operating currents and reduce the dependence of the LED parameters on temperature, as well as to increase the uniformity of radiation across the plane [11, 12, 13]. This makes it possible to significantly improve the degradation characteristics of the LED and significantly increase the service life of the optical radiation source. Replacing the LED in the pyrometer-reflectometer leads to precision adjustment of both the collimator itself and the device on special stands.

Taking into account the above, an LED on a quantum-sized multilayer AlGaAs/GaAs heterostructure with a light-emitting area diameter of 120 μm has been developed, with the following main parameters (Table 1).

Table 1. The main parameters of the developed AlGaAs/GaAs LED

Wavelength λ, nm	**Spectral Width[*1] Δλ, nm**	**Rise and Fall Time[*2] τ, ns**	**Optical Power[*3] P, mW**
Peak: 950 Centroid: 940	44	15	5

*1 Spectral width value at 0.5 level
*2 At pulse levels of 10% and 90%
*3 With a current through the LED of I = 10 mA

Conclusions

Based on theoretical analysis and the provided experimental studies, scientific and technical recommendations have been developed. These recommendations are aimed at selecting and optimizing the parameters of optoelectronic components of an infrared pyrometer-reflectometer (photodetectors, LEDs, and optical filters) in order to improve the accuracy of determining the actual wafer temperature during the formation of semiconductor heterostructures on its surface.

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ОСОБЛИВОСТІ РОЗРОБКИ ІНФРАЧЕРВОНОГО ПІРОМЕТРА-РЕФЛЕКТОМЕТРА ДЛЯ ОТРИМАННЯ НАПІВПРОВІДНИКОВИХ ГЕТЕРОСТРУКТУР

Для усіх типів реакторів для технології газофазної епітаксії з використанням металоорганічних сполук AIII-BV існують загальні технічні вимоги. Серед них варто виділити великі градієнти температури, що спричиняють виникнення конвекційний петель, які, в свою чергу, враховуючи високу швидкість газового потоку, призводять до турбулентності в реакторі замість очікуваного ламінарного потоку. Важливим також є врахування зміни параметрів поверхні пластини в процесі росту та необхідність розрізнення корисного сигналу з поверхні пластини та фонового сигналу з тримача пластин, що обертається для рівномірного осадження сполук.

Для отримання якісних гетероструктур з відтворюваними параметрами важливо мати систему точного контролю температури на поверхні пластини безпосередньо в області осадження, оскільки процес осадження для багатьох складних напівпровідникових приладів (наприклад, лазерні діоди, світлодіоди, фотодіоди, транзистори на гетеропереходах) дуже чутливий до змін температури. Метод оптичної пірометрії є безконтактним, що дозволяє прецизійно визначати температуру поверхні пластини та відповідає технічним вимогам ростових реакторів технології газофазної епітаксії.

Дана стаття присвячена особливостям розробки оптоелектронних систем для прецизійного вимірювання температури під час епітаксійного росту з метою визначення критеріїв для вибору або розробки компонент оптоелектронної системи пірометра-рефлектометра. В роботі досліджені основні фізичні процеси, електрооптичні характеристики Si фотодіода, AlGaAs/GaAs світлодіода та параметри смугових інтерференційних фільтрів.

На основі аналізу отриманих результатів досліджень і вимірювань розроблено наукові рекомендації щодо вибору та оптимізації параметрів компонентів пірометра (фотоприймачів, світлодіодів, оптичних фільтрів) з метою підвищення точності вимірювань та температурної стабільності вимірювання в умовах експлуатації пірометрів, які враховують компенсацію зміни випромінювальної здатності поверхні пластини.

Ключові слова: напівпровідники А3-В5; газофазна епітаксія з металоорганічних сполук; ГФЕ МОС; фотодіод; світлодіод; пірометрія з компенсацією випромінювання; оптико-електронні системи контролю параметрів; оптичний фільтр.

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