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Research on the Dynamic Range of Silicon Photodiodes for Optical Pyrometry Applications

D. O. Verbitskyi[f], 0000-0002-1295-9601
A. O. Voronko[s], PhD, 0000-0003-2899-963X
Department of microelectronics, me.kpi.ua
National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute» 00syn5v21
Kyiv, Ukraine

***Abstract*—Optical pyrometry is one of the main non-contact methods for precise temperature measurement of semiconductor wafers for vapour-phase epitaxy from metal-organic compounds (MOCVD). The requirements for the photocell of the pyrometer are due to the peculiarity of the process. In the pyrometer, the silicon photodiode operates in a mode that is characterized by a small bias voltage value, high sensitivity to weak light radiation, and low noise level. The main temperatures used in vapour-phase epitaxy technology depend on the semiconductor material being grown and the process parameters. Typically, process temperatures range from 500 to 1200 °C. A study of the dynamic range of a silicon photodiode for use in optical pyrometry was conducted. It was established that the minimum value of the dark current and the maximum value of the spectral sensitivity are key to obtaining the desired characteristics, namely, sensitivity to thermal radiation at a temperature of 450 °C. The peculiarities of the manufacturing technology of the planar-diffusion structure of the photodiode to achieve the necessary characteristics that ensure the production of photodiode structures with improved parameters are also considered.**

Keywords — silicon photodiode; optical pyrometry; vapour-phase epitaxy; dynamic range; dark current; spectral current sensitivity.

I. Introduction

In the process of gas-phase epitaxy from metal-organic compounds (MOCVD) for growing high-quality thin semiconductor epitaxy layers, it is important to observe the temperature conditions and regimes required by a specific technological recipe. Usually, temperatures in MOCVD technology are in the range from 500 to 1200 °C. For example, a temperature range of 700 to 800 °C [1] is used to grow GaAs thin films, 600 to 650 °C to grow InP, and more than 1000 °C to grow GaN. The exact temperature conditions depend on the specific MOCVD process, reactor characteristics, and requirements for the thin epitaxial layer to be grown, and may differ from the above values. To measure the distribution of temperature and thickness of epitaxial layers on the surface of the semiconductor plate during its rotation in the growth reactor, it is necessary to ensure the registration of a modulated optical signal with a cut-off frequency of 10 kHz.

The temperature repeatability required for the technology should be ± 0.4 °C. The necessary precision in the presence of thin epitaxial layers on the surface of the substrate, which change the optical parameters of the measuring surface, is provided by using the radiation compensation method. Compensation occurs by measuring the reflectivity of the surface using a reflecto meter [2]. The measured value of *R* makes it possible to compensate for the change in emissivity ε using the law of conservation of energy for optically opaque objects. However, the implementation of this method requires measurement in a narrow spectral range.

The choice of the optical measurement range is determined by the optical properties of the deposited material. In this article, the near-infrared range from 925 to 935 nm, selected with the help of an interference light filter with a maximum transmission at a wavelength of λ_c = 930 nm, and a transmission width of 50 % of the maximum at 10 nm, is considered as the spectral region of measurement.

A silicon p-n photodiode (PD) or a photo- and position-sensitive matrix assembly is mainly used as a sensitive element in these systems [3]. Due to the rotation of the plate holder in the reactor, measurement in a narrow spectral range and provision of a dynamic range sufficient for the task, certain requirements are placed on the photodetector (PD). It should have a minimum rise and fall time for operation with a modulated light

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flux with a frequency of up to 10 kHz and a high threshold sensitivity.

The dynamic range of a silicon PD at a given load resistance depends on its parameters:

The high ampere-watt sensitivity of the PD in the measurement area allows recording the near-infrared (IR) component of thermal radiation of lower intensity. This, in turn, improves the sensitivity threshold and dynamic range, as the PD can handle a wider range of energy illumination levels.

The level of shot noise, which is predominant in the noise composition, is determined by the level of the dark current and determines the minimum signal level that can be detected. The reduction of the noise component of the PD provides the possibility of detecting the near-IR component of low-power thermal radiation [4].

A simplified equivalent circuit of a PD (PD crystal with a connected load resistance, without applying a bias voltage to the p-n junction) at low frequencies is shown in Fig. 1.

The purpose of the research article is to determine methods of increasing the dynamic range of a silicon photodiode operating in the mode with minimal bias voltage, in particular, by reducing the dark current and obtaining high sensitivity in the area of measurements.

At a high level of optical radiation power (a high value of the photocurrent generated by optical radiation) on series-connected resistances $R_{посл.}$. and $R_{н}$ a voltage drop occurs. It reduces the height of the p-n junction barrier (reduces the value of $R_{вит}$). At the same time, the photocurrent is divided at point 1. This leads to the nonlinearity of the ampere-watt characteristic of the PD.

It is obvious that in order to improve the linearity of the ampere-watt characteristic of the PD, it is necessary to increase its sensitivity (provide higher values of the generated photocurrent in the range of low optical radiation power values) and reduce the values of the series resistance of the PD and the load resistance. However, the latter can always be implemented. The linearity of the ampere-watt characteristic in a wide range of light radiation powers allows the PD to determine the energy illumination in different wavelength ranges of light radiation with high accuracy. In those power ranges of light radiation, where there is a deviation of the ampere-watt characteristic from a linear dependence, its output signal is distorted. This leads to a limitation of the dynamic range of the photo-receiving device [5].

The rise time of the output photoresponse of the PD determines how quickly it can respond to changes in the level of energy illumination. The faster the photodetector (PD), the greater the dynamic range of the pulse signal amplifier can be achieved [3].

Cross-sections of PD crystals with different sizes of photosensitive elements (PSE) of the crystal are shown in Fig. 2. The dimensions of the PSE "a" and "a1", the thickness of the crystal bases W, the geometry of the contact pads to the PSE (frontal contact 6, Fig. 2) affect the linearity of its ampere-watt characteristic and the dynamic range of the amplifying device as a whole. It is known that the series resistance of the PD crystal consists of the resistance of its base W, the resistance of spreading in the diffusion region of the p-type (spreading in the PSE) and the resistance of the contact pads of the crystal. It is obvious that in the PD with a large area of the PSE (the size of the PSE), the base resistance is smaller, compared to the resistance of the base of the PD crystal with a small PSE area. However, the spreading resistance of the crystal with a smaller PSE area will be lower compared to the spreading resistance of the PSE crystal with a larger PSE area.

A PD crystal with a larger PSE area can detect minimum levels of illumination, but this is possible only at

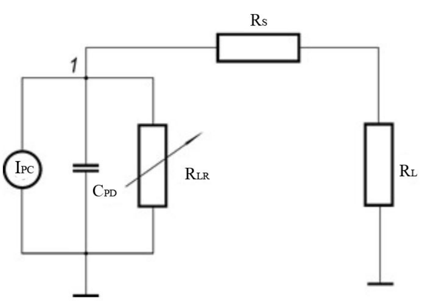

Fig. 1. Equivalent circuit of a photodiode

I_{PC} – photocurrent generator; C_{PD} – capacitance of the p-n junction; R_{LR} – leakage resistance; $R_{S.}$ – series resistance of the PD crystal; R_{L} – load resistance.

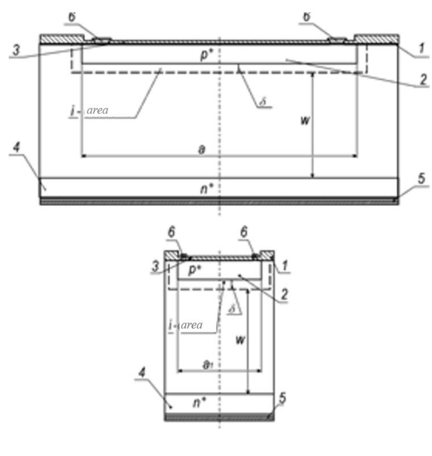

Fig. 2. Transverse sections of PD with different sizes of PSE

1 – protection layer, 2 – p+-type diffusion layer, 3 – antireflective coating, 4 – n+-type diffusion layer, 5 – back contact, 6 – front contact.

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a low level of its own noise (dark current). The low level of dark current of the crystal, in particular, is achieved by the peculiarities of the technological process of its manufacture [6]. It should be taken into account that the speed of operation of a crystal with a large PSE area decreases due to the increase in its electrical capacity. Based on the above, when designing a PD crystal, a certain compromise should be reached depending on the task it has to perform.

II. ANALYSIS OF THE DEPENDENCE OF CHARACTERISTICS ON DESIGN PARAMETERS

A. Dependence of the dark current

To express the dark current I_T, we can use the expression of the saturation current I_S, which is calculated for a p-n junction with a known size and regions that are thicker than the diffusion length of the carriers and depends only on the physical parameters of the semiconductor material in both regions of the transition:

$$j_s = e\left(\frac{p_n D_h}{L_h} + \frac{n_p D_e}{L_e}\right), \tag{1}$$

where e – the elementary charge of an electron; p_n, n_p – concentration of holes and electrons; D_h, D_e – diffusion coefficient of holes and electrons; L_h, L_e – diffusion length of electrons and holes.

For junctions with different degrees of doping, the saturation current density is primarily determined by the parameters of the area with higher resistance. In the case of a photodiode with a higher resistance in the *n*-type region, the equilibrium concentration of holes in the *n*-region p_n will be much greater than the concentration of electrons in the *p*-region. Then equation (1) can be simplified:

$$j_s = e\frac{p_n D_h}{L_h}.$$

Expression (1) assumes that the influence of minor charge carriers, thermally generated in the space charge region, can be neglected. However, this assumption can be used only for semiconductors with a large value of the equilibrium concentration and a small band gap (Ge, InSb). For semiconductors with a larger band gap, in particular silicon, it is necessary to take into account the space charge carriers formed in the layer. The current density j_g in this case is equal to:

$$j_g = \frac{e n_i \delta}{2\tau},$$

where δ – the thickness of the space charge region; τ – time constant.

Dark current density in semiconductors with a larger band gap, particularly for silicon, depends on the thickness of the space charge region δ, which depends on the voltage U applied to the p-n junction. Therefore, the dark current does not reach saturation, but increases in proportion to the growth of the bias voltage applied to the p-n junction. An increase in the width of the PD base layer also leads to an increase in the dark current level. The level of dark current is proportional to the cross-sectional area of the base layer [7]. The surface component of the dark current of the crystal cannot be neglected either. The surface component of the dark current is determined by the formula:

$$I_s = \frac{e n_i s_0 A_F}{2},$$

where n_i – intrinsic carrier concentration in silicon, s_0 – parameter describing the surface recombination characteristics, A_F – the area of the near-surface depleted zone.

The value of s_0 strongly depends on the quality of the processing and annealing operations of the silicon wafers from which the crystal is made. In practice, for PDs operated in the absence of a bias voltage applied to the p-n junction and at low values of the bias voltage, the decisive contribution to the dark current is made by its diffusion component. However, if it is necessary to obtain the minimum possible intrinsic noise of the PD, additional attention should be paid to reducing the values of the generation and surface components of the dark current.

B. Dependence of the spectral sensitivity

The sensitivity of the photodiode depends on the wavelength of the incident radiation λ. This dependence is characterized by spectral sensitivity. The higher the sensitivity of the PD, the smaller the light signal required to obtain its output photo signal [8]. PD can detect a wider range of energy illumination. The spectral sensitivity depends on the internal quantum efficiency of the crystal η_λ and the reflection of radiation by the surface of the crystal R_λ [9]:

$$S_\lambda = \frac{e}{hc}\lambda\eta_\lambda(1 - R_\lambda), \tag{2}$$

where e – the elementary charge of an electron; h – Planck's constant; c – speed of light; λ – wavelength of radiation; R_λ – surface reflectance; η_λ – intrinsic quantum efficiency.

In the ideal case, when all the light absorbed in the volume of the photodiode creates carriers that would be separated by the transition and participate in the photocurrent. In the meantime, the spectral sensitivity described by expression (2) would have the form of a straight line with an absorption edge corresponding to the absorption edge silicon. In an ideal case, the spectral sensitivity of silicon would be a straight line with a sharp transition to 0 at the edge of the absorption edge of silicon. However, as shown in Fig. 3, the spectral sensitivity of a real silicon photodiode differs from the ideal one, due to the spectral reflection coefficient R_λ and the curve

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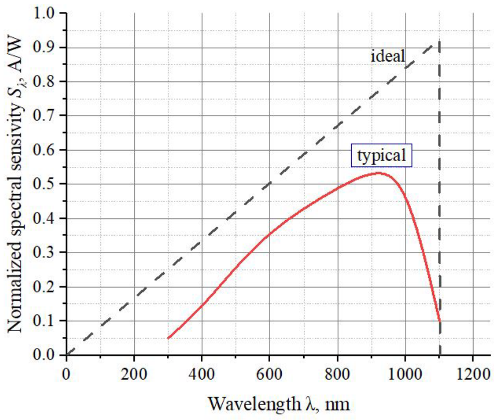

Fig. 3. Spectral sensitivity of real and ideal photodiodes

of quantum efficiency η_λ, which is determined by the construction of the p-n junction.

The reason for the decrease in the internal quantum efficiency of the PD crystal in the ultraviolet and near-visible region of the spectrum is the surface recombination of photogenerated charge carriers. In the near-infrared region of the spectrum the reason is the bulk recombination of carriers due to the insufficient length of the charge carrier run and the absorption of light by the rear side of the crystal [10]. An option for realizing a high value of the internal quantum efficiency is the use of epitaxial structures with a high-quality high-resistive layer with a high value of the life time of charge carriers for the manufacture of a crystal.

C. The aspects of manufacturing technology

The high sensitivity and low dark current of the crystal depend on several important technological and design factors. One of them is the selection of a silicon ingot with a high charge carrier lifetime. It is also important to select a silicon ingot with a small spread of specific resistance across the diameter of the ingot, which should be less than 5%. In addition, high-quality treatment of the surface of the silicon wafer also affects obtaining high sensitivity and low value of dark current.

Also, it is necessary to remove the damaged layer of the plate using the method of chemical dynamic polishing or deep etching. To clean the surface of the plate from metal ions, it is necessary to use salt-peroxide washing. All pickling and washing components must belong to the class of particularly clean substances. Water used for deionization must be constantly monitored for iron content.

In order to preserve the maximum life time of minority charge carriers, after the completion of thermal processes, slow cooling of the plates is necessary. The hetering of heavy metals from the bulk of the wafer during phosphor diffusion is very important, both for the dark current and for the sensitivity. At the same time, it is necessary to observe the conditions so that the diffusion length of the carriers is greater than the thickness of the crystal after all operations have been performed.

The wafer thickness should be optimal for maximum internal collection of photogenerated charge carriers. It is necessary to take into account the spectral dependence of the depth light absorption by silicon.

When operating the photodiode in the photovoltaic mode (without voltage bias) in the depth of the plate, near its reverse side, there is an area in which no photocarriers are generated. In this region, photocarriers will also move towards the p-n junction. However, for them, the diffusion n^+ region is a barrier that leads to the recombination of photocarriers in this zone and a decrease in sensitivity. Therefore, if the diffusion length of the photocarriers is long, then a significant part of them will be able to reach the p-n junction and contribute to the sensitivity of the photodiode.

III. Methodology of the experiment and discussion of the results

To study the dynamic range, photodiodes were manufactured, the value of the dark current (Table 1) was measured using an input block consisting of an amplifier circuit with the possibility of switching the gain (Fig. 4, Fig. 5). This circuit is based on a transimpedance amplifier with phase compensation.

The switching circuit, made on dual operational amplifiers, provides a gain change of up to 100 dB for scaling the signal before further ADC processing.

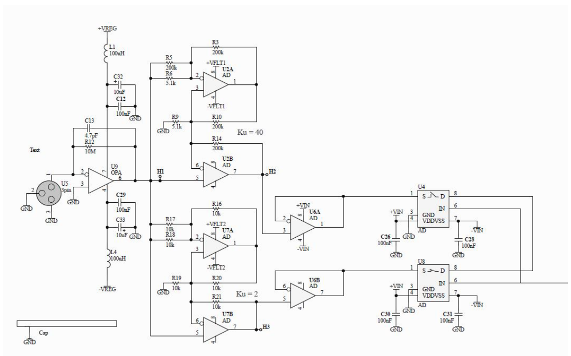

Fig. 4. Schematic diagram of an amplifier with a variable gain

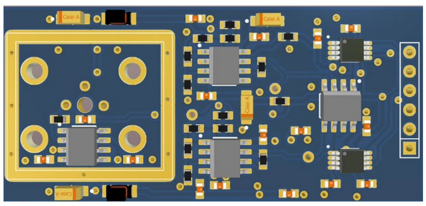

Fig. 5. The developed variable gain amplifier board

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TABLE 1 DARK CURRENT OF THE PHOTODIODES

Number of the photodiode	Dark current I_T, pA
1	24
2	19
3	12
4	28
5	11
6	20
7	16

a. Conditions of the measurements ($U_{зм}$ = 10 mV, T = 20 °C)

TABLE 2 CURRENT SIGNAL OF THE PHOTODIODE

Temperature of the blackbody, °C	Photocurrent signal I_S of the photodiode, nA
450	0.03
475	5.195
500	10.36
525	15.525
550	20.69
575	25.855
600	31.03
625	36.195
650	41.36
675	46.525
700	51.70
725	56.855
750	62.03
775	67.195
800	72.36
825	77.525
850	82.70
875	87.855
900	93.00

For further research, photodiodes with the lowest value of the dark current and a linear ampere-watt characteristic were used. Spectral sensitivity was measured by comparison with a reference photodiode. The average value of sensitivity in the region of 930 nm was 0.57 A/W, and the rise time τ at a load of R_L = 1 kΩ was 2.5 µs. The input offset voltage of operational amplifier was 70 uV, input bias current was 3 pA, input voltage noise density was range 4 nV / Hz$^{1/2}$ at 1 kHz, 3.8 nV / Hz$^{1/2}$ at 10 kHz.

The technique for measuring the dark current was that the sensitive region of the PD was isolated from light radiation in a light-tight chamber equipped with a thermostat to maintain a stable temperature. To reduce noise, an electrochemical cell with subsequent voltage stabilization was used as a bias voltage source. The value of the bias voltage was 10 mV. The current signal was converted into a proportional output voltage and recorded by an ADC.

To measure the dependence of photocurrent on temperature, a temperature-stabilized absolutely black body was used, the temperature of which varied in the range from 450 to 900 °C. An interference filter with a central wavelength λ_C = 930 nm and a half-width Δλ = 10 nm was located at the input of the PD. A BASF precision pyrometer was used as a control temperature meter. Measurements were made at a distance of 20 cm, with a blackbody aperture with a diameter of 0.5 cm. The results are presented in Table 2.

The study of the linearity of the PD photocurrent depending on the intensity of the incident radiation was carried out at a wavelength of 930 nm.

Based on the results of the research, we can say that at the measurement wavelength of 930 nm, the thres hold value of the object temperature for optical pyrometry was 450 °C, but the signal-to-noise ratio has an acceptable level at a temperature of 500 °C. With the help of design optimization, this value can be increased.

For lower-temperature measurements of objects up to 400 °C in the near-infrared range, it is advisable, depending on the specific task, to use a longer wavelength due to higher thermal radiation intensity. Additionally, a photodetector with maximum sensitivity in this range is preferred. In the case of optically transparent objects in the IR spectrum, UV-sensitive photodiodes can also be employed for temperature determination [11].

CONCLUSIONS

The article deals with a silicon p-n photodiode used as a sensitive element in a pyrometer-reflectometer for gas-phase epitaxy. The main requirements for the photodetector were analyzed: the rise and fall time for working with modulated radiation with a frequency of up to 10 kHz, monochromatic current sensitivity in the measurement area, and the value of the dark current.

The shape of the spectral current sensitivity of the silicon photodiode is determined by the reflection coefficient of radiation from the surface R_λ. The internal quantum efficiency ηλ, which is determined by the p-n junction design, affects the sensivity as well.

The values of the dark current and spectral sensitivity parameters depend on technological factors. Among them, in order to achieve the minimum value of the dark current and the maximum value of the spectral sensitivity in the region of more than 900 nm, the planar diffusion technology requires the use of high-quality silicon wafers with a large value of the diffusion length. This will lead to an increase in spectral sensitivity and a decrease in the generation noise component.

Photodiodes were manufactured, among which were selected for further research based on the criterion of the lowest value of the dark current and the maximum spectral sensitivity in the measurement area. Studies have shown that the temperature threshold value for a silicon photodiode with an operating wavelength of 930 nm is 450 °C. At a value of 500 °C, it meets the conditions for using a silicon p-n photodiode as a sensitive

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element for control systems of the gas-phase epitaxy process.

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Дослідження динамічного діапазону кремнієвих фотодіодів для застосування в оптичній пірометрії

Д. О. Вербіцький[f], 0000-0002-1295-9601
А. О. Воронько[s], к.т.н., 0000-0003-2899-963X
Кафедра мікроелектроніки, me.kpi.ua
Національний технічний університет України
«Київський політехнічний інститут імені Ігоря Сікорського» 00syn5v21
Київ, Україна

***Анотація*—Оптична пірометрія є одним з основних безконтактних методів для прецизійного вимірювання температури напівпровідникових підкладок для технології газофазної епітаксії з металоорганічних сполук (ГФЕ МОС). Вимоги до фотоелементу пірометра обумовлені особливістю процесу. У пірометрі кремнієвий фотодіод функціонує в режимі, який характеризується невеликим значенням напруги зміщення, високою чутливістю до слабкого світлового випромінювання та низьким рівнем шумів. Основні температури, які використовуються в технології газофазної епітаксії, залежать від матеріалу напівпровідника, який вирощується, та від параметрів процесу. Зазвичай, температури процесу знаходяться в діапазоні від 500 до 1200 °С.**

В даній статті розглянуто кремнієвий p-n фотодіод, який використовується як чутливий елемент в пірометричній системі контролю. Вимогами до фотодетектора є достатній час наростання і спаду для роботи з модульованим світлом з частотою до 10 кГц, що обумовлено обертанням тримача пластин в реакторі, висока монохроматична ампер-ватна чутливість в області вимірювання і мінімальне значення темнового струму. Показано, що спектральна струмова чутливість кремнієвого фотодіода визначається коефіцієнтом відбиття випромінювання від поверхні $R\lambda$ і внутрішнім квантовим виходом η_λ, який визначається конструкцією переходу.

Значення темнового струму і ампер-ватної спектральної чутливості фотодіоду залежать від конструктивно-технологічних факторів. Для досягнення мінімального значення темнового струму та максимальної спектральної чутливості в діапазоні понад 900 нм, для планарно-дифузійної технології необхідні високоякісні кремнієві пластини з великою дифузійною довжиною. Це призводить до підвищення спектральної чутливості та зменшення шумової складової генерації струму.

В ході роботи були отримані фотодіоди, серед яких для подальших досліджень були відібрані ті, що мають найменше значенням темнового струму і максимальною ампер-ватною чутливістю на робочій довжині хвилі вимірювання. Дослідження показали, що температурний поріг для кремнієвого фотодіода з робочою довжиною хвилі 930 нм становить 450 °С. Аналітичні та емпіричні дослідження дозволяють покращити характеристики систем контролю температури для технології газофазної епітаксії. Також отримані результати сприяють розробці технології отримання фотоприймачів з покращеними характеристиками. У цьому випадку це дає змогу підвищити точність вимірювання температури поверхні пластин і контролю параметрів в процесі газофазної епітаксії, що в свою чергу призводить до підвищення ефективності самого процесу MOCVD.

Ключові слова — кремнієвий фотодіод; оптична пірометрія; газофазна епітаксія; динамічний діапазон; темновий струм; спектральна струмова чутливість.