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Photodiode based on epitaxial silicon with high sensitivity at the wavelength 254 nm

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Abstract. A mathematical model of the construction of silicon photodiode based on epitaxial structure enabling to regulate the absorption edge of silicon in the long-wave spectral range is presented. The suggested model allows calculating the construction that possesses low sensitivity for the wavelengths larger than 600 nm and maximal values near the wavelength 254 nm.

Keywords: photodiode, silicon, sensitivity, ultraviolet radiation.

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1. Introduction

Silicon is hi-tech material for obtaining semiconductor devices including photodiodes. In this research, the possibility of using silicon photodiodes in ultraviolet (UV) radiometers is considered.

In terrestrial UV radiometers, the photodiodes with sensitivity within the range 200 to 380 nm are used. Such photodiodes have to be characterized by high sensitivity and a wide dynamic range. The photodiodes based on gallium phosphide, gallium nitride and zinc selenide meet these requirements. Technology of producing these photodiodes is more sophisticated than, e.g., technology of silicon photodiodes.

Within the spectral range 200 to 380 nm, the sensitivity of silicon photodiode reaches high values. It can exceed the sensitivity of photodiodes based on gallium phosphide or zinc selenide [1]. On the other hand, it is known that photodiodes based on silicon are sensitive in the near infrared spectral range. However, this sensitivity cannot be confined to zero by using light filters.

We have already considered and suggested constructions of photodiodes based on silicon epitaxial structures [2, 3]. The sensitivity of these structures was determined in the visible spectral range. That is why it was suggested to choose the thickness of the epitaxial layer equal to the absorption depth of visible light. The research work of A. Malik [4, 5] was used as the foundation for the development of photodiodes based on gallium phosphide for ultraviolet spectrum. Later in [1, 7], it was shown how the increased values of sensitivity at the wavelength 254 nm can be obtained for ultraviolet photodiodes.

Using the previous experience, the mathematical model of the construction of silicon photodiode based on the epitaxial structure enabling to regulate the absorption edge of silicon in the long-wave range of spectrum is suggested in this research. This construction will allow obtaining the silicon photodiodes that have sensitivity only in the ultraviolet spectral range.

The construction of a random photodiode is calculated using the system of inequalities that includes the following parameters:

h – propagation depth of electric field due to the concentration gradient of charge carriers at the boundary "epitaxial silicon – low-resistance substrate";

h_{el} – thickness of epitaxial layer;

x_0 – length of the space charge region in epitaxial layer generated by the barrier between semiconductor and the conducting metal oxide layer.

L_p – diffusion length of holes in epitaxial layer;

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α_λ – absorption coefficient of radiation with the given wavelength in semiconductor;

d – thickness of the silicon oxide layer;

n – refraction index of the metal oxide film;

$S_{I\varphi}$– sensitivity caused by optical radiation falling on photodiode;

I_{ph} – specific value of photocurrent generated by a single plate providing sensitivity of photodiode at the given wavelength;

P – power of incident optical radiation;

S – area of photosensitive element.

It is obvious that, through regulating the thickness of the epitaxial layer, it is possible to regulate the long-wave absorption edge of the photodiode structure on the whole. While developing such a structure, the main problem consists in accurate calculation of the absorption depth of the longest-wave radiation that is to be registered by the device.

It is shown in [1] that while providing certain constructive and technological requirements, it is possible to make photodiodes based on silicon with the value of current monochromatic sensitivity not lower than 0.1 A/W at the wavelength 300 nm and the value 0.13 A/W – at the wavelength 250 nm (Fig. 1). Photodiodes of the "Quantum" type are normalized at the wavelength 550 nm. At this wavelength, the value of current monochromatic sensitivity amounts to 0.29 A/W, while at the maximum of spectral sensitivity it is 0.44 A/W [1, 9].

The disadvantage of silicon photodiodes, including those of the "Quantum" type, from the viewpoint of their application in ultraviolet radiometry, as it was mentioned above, consists in their sensitivity in the infrared spectral range.

Computer modeling shows that the suggested construction of a photodiode based at silicon epitaxial structure with thin basis can provide current monochromatic sensitivity at the wavelength 254 nm not lower than 0.05…0.09 A/W. The results of modeling have been presented in Fig. 2. Here, only the part of sensitivity caused by the absorption depth of optical radiation with different wavelengths was considered [10].

Investigations carried out in [11] show that, in the operating range of wavelengths (200 to 500 nm), practically total absorption of optical radiation occurs (up to 86% of radiation fallen on the semiconductor layer) in the layer with the thickness close up to 1.5 μm. The discrepancy between the calculation data (Fig. 2) can be explained by the fact that in the case of calculation, only absorption of optical radiation in silicon was taken into account without considering the properties of material, antireflection coating and many other.

Being based on the research, the conclusion can be made that the construction of photodiode including the epitaxial structure of n^+-n-type, in which the high-resistance layer of n-type, located on the low-resistance substrate, is the operation layer (where absorption of optical radiation occurs).

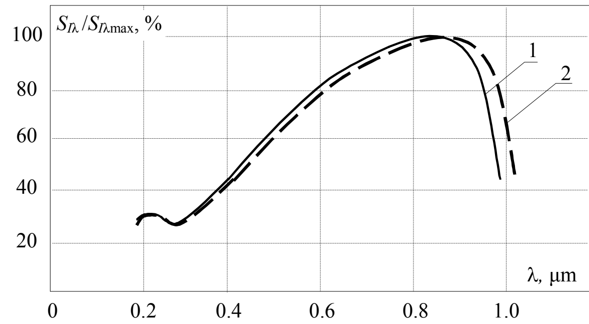

Fig. 1. Relative spectral characteristics of sensitivity of silicon photodiodes. 1 – "Quantum"; 2 – "Quantum-1".

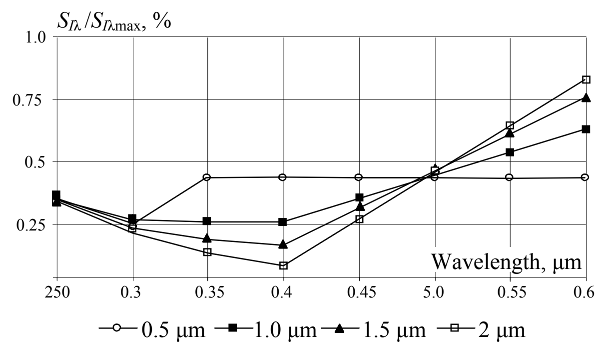

Fig. 2. Calculated values of relative spectral characteristics of sensitivity of silicon photodiodes based on epitaxial structures of different thicknesses.

To determine the highest possible value of sensitivity that can be obtained in this case, we shall use the approach described in [6, 7]. Here, to provide maximal sensitivity of the photodiode structure, it is suggested to solve the system of inequalities that includes the main parameters of the photodiode construction and physical parameters of material.

The main contribution to the photo-signal in this structure is made by minority carriers, thus, the L_p value will be determinative in the structure n-n^+. It should be mentioned that not only L_p determines the depth of the region for collection of photo-generated charge carriers, but also the length of the space charge region in epitaxial layer x_0, generated by the barrier between n and p regions forming the p-n junction in the epitaxial layer.

The concentration of dopants in the epitaxial layer of h_{el} thickness exponentially decreases moving from the boundary "substrate – epitaxial layer" as a result of autodoping processes [11]. Thus, it contains electrical field caused by the distribution profile of dopant concentration [12]. The depth of propagation of this field should be also considered while calculating h_{el}. Therefore, the thickness of the epitaxial layer can be determined using the following inequality:

$$x_0 < h_{el} \leq (L_p + x_0 + h). \quad (1)$$

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It is evident that the low-resistance substrate of the epitaxial structure should not affect sensitivity of the device. This requirement is provided by inequality (2):

$$L_p < (h_{el} - x_0). \quad (2)$$

To provide collection of charge carriers generated by short-wave optical radiation, it is necessary that the length of the space charge region x_0 in the high-resistance layer should be longer than the absorption depth of this radiation. This absorption depth, in its turn, is determined by the absorption coefficient of this radiation α_λ (in cm^{-1}) and is shorter than the diffusion length of minority carriers (in our case – holes). These requirements are provided by the inequality:

$$\alpha_\lambda < x_0 \le L_p. \quad (3)$$

Uniting the suggested expressions into a system enables to optimize the construction of epitaxial silicon photodiodes that operate in the photovoltaic mode to guarantee maximal sensitivity:

$$\begin{cases} x_0 < h_{el} \le \left(L_p + x_0 + h\right), \\ L_p < \left(h_{el} - x_0\right), \\ \alpha_\lambda < x_0 \le L_p. \end{cases} \quad (4)$$

The first expression determines the region of collecting the carriers photo-generated by the long-wave component of the region of photodiode spectral sensitivity; the second one provides isolation of the high-resistance epitaxial layer from the impact of charge carriers generated in the low-resistance substrate of the epitaxial structure; the third expression provides contribution of the short-wave component of the spectrum.

To guarantee maximal sensitivity of the photodiode, in addition to the above mentioned procedures, it is necessary to consider the reflection phenomenon of the optical radiation flux from the surface of the optically transparent antireflection coating of silicon dioxide.

The right choice of silicon dioxide thickness enables to minimize losses in photocurrent, related to the fact that a part of the optical radiation flux capable to generate minority charge carriers in semiconductors is reflected from both the surface of silicon dioxide and that of semiconductor. The thickness of the silicon dioxide layer d is selected with account of the condition that the phase difference φ of radiation at the round-trip passage through the layer is to be multiple $(2n+1)\pi$. In the opposite case:

$$d = \lambda(2n+1)/4. \quad (5)$$

In this case, the waves reflected from the boundaries “film – air” and “film – semiconductor” will be added in the antiphase and “suppress” each other [12].

The area of the photosensitive element should be also taken into account, as the value of photocurrent, provided that the whole plate of photodiode is illuminated by the radiation flux P, can depend on it.

$$I_{\text{ph}} \cong \frac{S_{I\varphi} P}{S} \text{ or } I_{\text{ph}} S \cong S_{I\varphi} P. \quad (6)$$

Thus, the system of inequalities (4) can be transformed into the system of inequalities and equations:

$$\begin{cases} x_0 < h_{el} \le \left(L_p + x_0 + h\right), \\ L_p < \left(h_{el} - x_0\right), \\ \alpha_\lambda < x_0 \le L_p, \\ d = \lambda(2n+1)/4, \\ I_{\text{ph}} S \cong S_{I\varphi} P. \end{cases} \quad (7)$$

The value of current monochromatic sensitivity at a certain wavelength can be also assessed using the results obtained in [13]:

$$S_{I\lambda} = \left(1 - R_{1\lambda}\right) \frac{e_0 \gamma_\lambda \lambda}{hc} \left(1 - e^{-\alpha_\lambda x_0}\right), \quad (8)$$

where $S_{I\lambda}$ is the current monochromatic sensitivity for the given wavelength; $R_{1\lambda}$ – coefficient of reflection from the surface “air – oxide – semiconductor” for the given wavelength; λ – given wavelength; γ_λ – photocurrent utilization coefficient (inner photo-response); h – Planck constant; c – speed of light in vacuum; e – elementary electric charge.

To reach that, (8) should be divided by the thickness of the metal oxide film:

$$\begin{aligned} S_{I\lambda} &= \left(1 - R_{1\lambda}\right) \frac{e_0 \gamma_\lambda \lambda}{hc} \left(1 - e^{-\alpha_\lambda x_0}\right) \Big/ d = \\ &= \left(1 - R_{1\lambda}\right) \frac{4 e_0 \gamma_\lambda}{hc(2n+1)} \left(1 - e^{-\alpha_\lambda x_0}\right). \end{aligned} \quad (9)$$

Analysis of the obtained equations and inequalities (7) and (9) performed by means of MS Office Excel 2003 showed (Fig. 3) that the maximal values of sensitivity at the wavelength 250 nm can reach 0.08–0.09 A/W, if the epitaxial layer thickness is 1.5 – 2 μm. The calculation was based on the values α_λ, γ_λ, $R_{1\lambda}$ and n presented in [13]. The value x_0 was assessed in 0.1–0.3 μm, it accounting the fact that the photodiode should operate in the photovoltaic mode without electrical bias. The length of the space charge region in this case is conditioned by the potential barrier between p and n layers and epitaxial silicon substrate.

The analysis results prove that the best values of sensitivity in the ultraviolet spectrum can be obtained at the epitaxial layer 1.5-μm thick. It is a complicated technological task requiring accurate equipment that enables to form *p-n* junction with the accuracy close to 0.1 μm.

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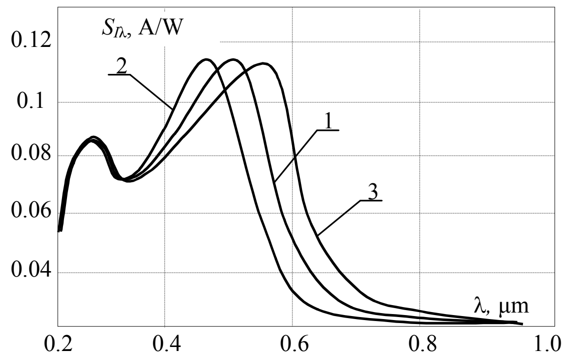

Fig. 3. Dependence of the calculated values of the current monochromatic sensitivity of silicon photodiode on the epitaxial layer thickness: h_{el} = 1 µm (*1*), 1.5 µm (*2*), 2 µm (*3*).

The best of the well-known analogues possess the current monochromatic sensitivity value 0.08…0.07 A/W at the wavelength 250 nm. However, these are the devices based on gallium phosphide and zinc selenide. These materials are more expensive than epitaxial silicon. On the other hand, technological processes on silicon are generally more manufacturable, more well-tested in serial production, which provides a possibility for a low price for these photodiodes in batch production.

It should be indicated that the suggested report does not consider these characteristics influencing sensitivity photodiode, as the surface-state density on the surface of silicon epitaxial structure. The analytical consideration of this factor demands further investigation.

Conclusions

The mathematical model for calculating the value of current monochromatic sensitivity of silicon photodiode based on epitaxial structure for operation in the ultraviolet spectral range has been developed. The suggested model enables to calculate the construction having low sensitivity for the wavelengths longer than 600 nm and maximal values at the wavelength 254 nm.

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