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MODEL AND ALGORITHM OF CREATION OF SILICON PHOTODIOD WITH HIGH SENSITIVITY IN THE MIDDLE INFRARED AREA OF THE SPECTRUM

*The sensitivity of the photodiode will depend on the amount of radiation power that it must register. The characteristics of a photodiode, as is known, are determined by its design. In particular, the characteristics of the material used, the configuration of electric fields, the mobility of charge carriers, the width of the SCR (space charge region), etc. Additionally, the characteristics of the photodiode are determined by the external applied voltage and the wavelength of the received optical radiation. In the case of its absorption only in the SCR (region of space charge) and at small distances around it, for example, in a p-i-n photodiode, its frequency characteristics will be determined mainly by the flight time of the generated charge carriers through the SCR. .**The subject is to create** an algorithm for building a photodiode, which must work at a certain wavelength, for example, at a wavelength of 0.95 μm. Silicon of the p-type conductivity with a specific resistance of at least 10 kΩ • cm was chosen as the starting material. **The goal is** to create a model and algorithm for developing a photodiode capable of providing maximum values of current monochromatic sensitivity due to the maximum collection of photogenerated charge carriers in its volume at the appropriate external bias. **Task:** To fulfill this requirement, theoretical and experimental research must be conducted. **Methods:** technological processes for manufacturing the proposed photodiode can be similar to the processes of forming planar p-i-n photodiodes based on silicon. The proposed technical solution determines the correlation between the area of collection of photogenerated charge carriers and the area of their generation. The result can be achieved by changing the design of the photodiode crystal, considering the obtained theoretical conclusions. **Results:** An analysis of the factors determining the current monochromatic sensitivity of the photodiode was carried out. A design of a photodiode with increased sensitivity compared to a serial photodiode of the FD - 309 type has been developed. **Conclusions:** The proposed calculation was used to estimate the sensitivity of the photodiode. The operating voltage and, accordingly, the width of the OPZ (area of space charge) W was chosen considering the absorption depth of the operating wavelength of 0.95 μm. The calculation shows that the current monochromatic sensitivity of such a photodiode can be increased to 0.57 A/W in contrast to the declared sensitivity of 0.5 A/W. Comparative studies of the produced batch of created photodiodes and FD - 309 photodiodes were conducted, which showed that the proposed photodiode really has a current monochromatic sensitivity at a wavelength of 0.95 μm not less than 0.55 A/W. Simultaneously, its rise time is reduced from 50 ns to 10 ns, and the capacitance is 90 pF instead of 100 pF in FD - 309.*

Keywords: *Photodiode; silicon; wavelength; monochromatic; space charge region (SCR); infrared (IR).*

Introduction

Detection of light fluxes, in particular monochromatic radiation fluxes, has been and remains an urgent task of electronics and lighting. To solve this problem, in particular, photodiodes created on the basis of various semiconductor materials are used. The required material to create a photodiode is selected taking into account the width of its band gap, which determines its long-wavelength limit of absorption of optical radiation. Accordingly, the spectral sensitivity range of the material should correspond to the spectral sensitivity range of the photodiode. In this case, when the photodiode operates at a certain wavelength, this wavelength must be within the sensitivity of the photodiode. Of course, the sensitivity of the photodiode will depend on the amount of radiation power that it must register [1]. The characteristics of the photodiode are known to be determined by its design. In particular, the characteristics of the material used, the configuration of the electric fields, the mobility of the charge carriers, the width of the space charge region (SCR), etc. In addition, the characteristics of the photodiode are determined by the external applied voltage and the wavelength of the optical radiation received by the photodiode. In the case of its absorption only in the SCR (space charge region) and at negligible distances around it, for example, in the p-i-n photodiode, its frequency characteristics will be determined mainly by the time of flight of the generated charge carriers through the SCR (space charge region).

When developing silicon photodiodes, it is also necessary to ensure maximum sensitivity with a minimum noise level of the device, ie to ensure a high level of threshold sensitivity, which is largely determined by the dark current of the photodiode.

State of the Art

There are several ways to increase the sensitivity of the photodiode. It can be increased by reducing the recombination of charge carriers, as proposed in [2]. The absence of grain boundaries reduces the recombination of charges and provides a linear response in bright light [3].

[4] Proposes a bulk organic heterojunction consisting of a low-band non-fullerene and a polymer that provides broadband response spectra of up to 1 μm with a maximum external quantum efficiency of approximately 54% at 850 nm. The main disadvantage of the design is the high cost of its manufacture.

Photodetectors of the n+-p type, made of hyperdoped silicon prepared by ion implantation and a femtosecond pulsed laser, demonstrated a significant improvement in absorption and photoresponse at near-infrared (IR) wavelengths. The device, manufactured with an implantation dose of 10^{14} ions/cm^2, showed the best results [5]. However, at such a high dose of implantation, the dark currents of the photodiode should significantly deteriorate.

In [6], a silicon sensor of ultraviolet radiation with more than 90% intrinsic quantum efficiency (CE) and high selectivity to the UV (ultra violet) band without the use of optical filters is presented. The sensor is designed for applications that require UV (ultra violet) measurement under strong background visible and near-infrared light, such as solar measurement. The sensor consists of monolithically formed silicon photodiodes with different spectral sensitivity: a high-sensitivity to ultraviolet light photodiode with an internal KE of almost 100% for UV (ultra violet) light and a photodiode with a low level of sensitivity to ultraviolet rays of 10% with internal. The photodiodes were optimized according to their sensitivity to visible and infrared light, and the UV (ultra violet) signal is extracted from the background radiation by the method of differential spectral response. With this approach, an internal KE of more than 90% for UV light was obtained, with a residual internal KE for non-UV (ultra violet) light below 20% for 400 nm, 5% for 500 nm, 2% for 600 nm, and 0.6% for IR (infrared). light [6].

High-sensitivity metal-insulator-semiconductor (MIS) diodes with a positive photo response are fabricated by introducing polycrystalline composite thin films of Ce-WO_3 as an interfacial layer (IL) between the metal (Cu) and the semiconductor (p-Si) [7]. Ce-WO_3 films were successfully grown on a quartz substrate with 0.4, 8 and 12 wt. % Ce at an optimized base temperature of 400 °C. The inclusion of Ce atoms in the WO_3 matrix promoted better optical [20] absorption. A significant sensitivity of 20.61 mA/W was recorded on these structures. But such operations complicate the design and technology of the photodiode, which increases the cost of the product.

You can use as a starting material fullerene C60 [8] or graphene [9]. However, the operating time of such photodiodes is small, and the material itself is expensive. The best solution, in our opinion, is to optimize the design of the photodiode taking into account the peculiarities of its operation, as done in [10 - 14].

The study of known technical solutions shows that the available methods of increasing the sensitivity of the photodiode in the IR (infrared) region of the spectrum, listed above, have a certain effect. But they also have certain shortcomings that need to be addressed or improved.

On the other hand, there are known methods of modeling the structure of the photodiode to increase its sensitivity, methods of mathematical and software modeling. In particular, [15] developed analytical equations for estimating the magnitude of the photocurrent generated under different operating conditions of the photodiode [16, 17], and [15] showed the results of developing a stationary physical-topological model of p–i–n - photodiode, which is based on drift-diffusion carrier transfer scheme. charge in multilayer heterostructures based on $In_xGa_1 - xAs_y$ taking into account the Fermi-Dirac distribution function for electrons and holes, the dependence of the alloying impurity mobility and the electric field strength, as well as thermoelectron emission and tunneling of charge carriers at hetero boundaries.

Computer simulation of avalanche photodiode design was performed in [18]. The pulse behavior of a single photon has been studied after calculating the sensitivity of an avalanche photodiode [19]. The phenomenon of negative differential capacitance of p-i-n InGaAs/INP photodetectors has also been studied, which becomes more obvious with decreasing frequency [20]. In the article [21] the influence of the effective potential barrier on the capacitance, feedback and photodiode capacitance is studied.

To increase the sensitivity of the photodiode in a model of general fixing processes for 3-D attached photodiodes is presented, which can be used to model photodiodes with small dimensions by calculating the charge in the space charge (SCR) and investigates the mechanism of depletion of the internal region. SCR (space charge region) is analytically extracted.

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Objectives

As can be seen from the literature analysis, today, among the models and algorithms for developing photodiodes operating in the near-infrared region of the spectrum, factors that affect the sensitivity of the photodiode are taken into account, such as residual sensitivity after photodiode irradiation. However, among the known works, the effect on the sensitivity of the photodiode of the depth of the barrier region between different regions of conductivity of the photodiode, which actually form the p-n junction, is not considered. This region is formed due to the difference in the concentration of charge carriers in the doped region and the region of intrinsic conductivity.

Therefore, the aim of the study is to develop a model and algorithm for creating a silicon photodiode with high sensitivity in the near infrared region of the spectrum, taking into account the difference in the concentration of charge carriers in the doped region and the region of intrinsic conductivity.

Model

As a model, consider a p-i-n photodiode based on p-type silicon conductivity with a resistivity of at least 10 kO•cm This material is able to provide small values of photodiode capacitance and maximum collection of photogenerated charge carriers in its volume at a corresponding external offset in the near infrared region of the spectrum due to the fact that silicon has a band gap of 1.1 eV, accordingly, its red border the photoeffect (λ_{max}) reaches 1.1 µm.

Consider the possible design of the proposed photodiode used for calculations, a schematic representation of the section, which is shown in Figure 1. In general, the proposed design corresponds to the design of a standard p-i-n photodiode made by planar technology, in which the p-n junction is created by boron diffusion into silicon. But it does not consider the influence of protective rings and areas that are usually located outside the photosensitive area.

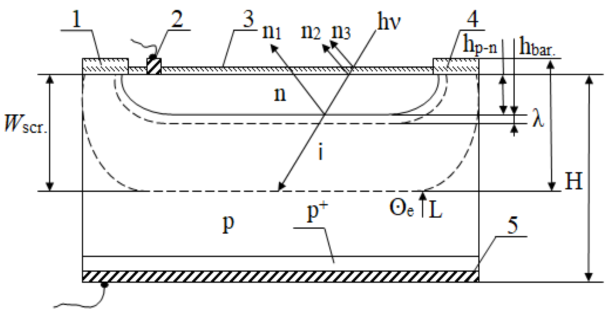

Fig. 1. Schematic representation of the cross section of the structure of the proposed photodiode

In Figures 1: 4 – protective thick layer of silicon oxide, 2 - metal ohmic contact, 3 - translucent layer of silicon oxide, 5 - ohmic contact to the reverse side of the photodiode. n, i, p, p + - designation of photodiode regions with corresponding conductivities.

Optical radiation of different wavelengths penetrates into silicon at different depths. The decrease in its intensity, according to the law of absorption of optical radiation, in e (2.7) times occurs at a depth of $1/\alpha$, where α is the coefficient of light absorption (hereinafter the depth of absorption). In particular, when a silicon photodiode is illuminated by monochromatic radiation with a wavelength of ~ 1 µm, its absorption is mainly carried out at a depth of 1 mm - 1000 times longer than the wavelength.

It should be noted that the thickness of the semiconductor substrate of the photodiode should not exceed the sum of the absorption depth of the working wavelength and the diffusion length of non-basic charge carriers, ie inequality (1) must be satisfied:

$$H \leq 1/\alpha + L, \quad (1)$$

where H is the thickness of the semiconductor substrate of the photodiode;

$1/\alpha$ - depth of absorption of the working wavelength;

L is the diffusion length of non-basic charge carriers.

Given that the diffusion length of non-basic charge carriers in silicon can reach several hundred microns, and the width of the space charge region, depending on the operating voltage and concentration of non-basic charge carriers, can reach from several tens to several hundred micrometers, the thickness of the crystal can be limits, however, it should be no more than the sum of the depth of radiation absorption of the working wavelength and diffusion length of non-basic charge carriers (1) and no more than the sum of the width of the space charge, diffusion length of non-basic charge carriers, and depth pn junction [20].

In addition, it is necessary to take into account the depth of the barrier region, which is formed at the boundary of the regions of p- and n-type conductivity due to the difference in the concentration of charge carriers in the doped region (n-type conductivity in Fig. 1) and the region of intrinsic conductivity. type of conductivity in Fig. 1. The width of such a region can be from 0.3 to 1 µm depending on the depth of the p-n junction and the average concentration of impurity charge carriers, which are formed during the diffusion of boron into silicon.

Therefore, the above requirements can be met by performing inequality (2):

$$H \leq W + h_{p\text{-}n} + h_{bar.} + L, \quad (2)$$

where W is the width of the SCR (space charge region);

L is the diffusion length of charge carriers;
h_{p-n} - depth of p-n junction;
h_{bar} is the depth of the barrier region.

Thus, to ensure the maximum sensitivity of the photodiode for measuring monochromatic light fluxes, it is necessary that the thickness of the semiconductor substrate of the photodiode H, the diffusion length of non-basic charge carriers L, the depth of the barrier region hbar, the depth pn junction hp-n and the width SCR (space charge region) system of inequalities (3):

$$\begin{cases} H \le 1/\alpha + L, \\ H \le W + h_{p-n} + h_{bar} + L. \end{cases} \quad (3)$$

It is also worth considering the mode of operation of the photodiode at high wavelengths, such as the wavelength of a laser based on yttrium-aluminum garnet (YAG) - 1064 nm, which is less than the red limit of the photoelectric effect in silicon and is widely used in optoelectronics. According to equation (1), when operating at such a wavelength, at a depth of p-n junction of 3 - 5 μm, and a depth of absorption of the working wavelength of 1.064 mm, the crystal thickness of the photodiode should be approximately 1.1 mm. In this case, the entire i-region of the photodiode of this thickness will give large values of dark current. In addition, the capacitance of the photodiode will also depend on its thickness. Therefore, when working at such a wavelength, the photodiode crystal is made twice as thin, and the contact on the reverse side is solid and mirror, which allows the use of double passage everywhere of the radiation beam crystal.

Therefore, the system of equations (3) should be supplemented by an appendix that relates to the above circumstances - the operation of the photodiode at a wavelength close to the red limit of the photoeffect

$$\begin{cases} H \le 2/\alpha + L, \\ H \le W + h_{p-n} + h_{bar} + L. \end{cases} \quad (4)$$

Algorithm

Thus, taking into account the above calculations, we can propose the following algorithm for calculating the design of a photodiode with high sensitivity in the near-infrared region of the spectrum, shown in Figure 2.

Therefore, at the beginning of the calculation it is necessary to determine the operating wavelength of optical radiation. In the case of using silicon as a source material, the analysis of its spectral sensitivity characteristics shows that at a wavelength of more than 1 μm the depth of radiation absorption in it increases significantly. Therefore, since the working wavelength is greater than 1 μm, the calculation is performed on the left branch of the algorithm. As smaller as possible, then according to the right branch. In both cases, the depth of the barrier region hbar is taken into account.

Using the created algorithm, consider the design of a photodiode that must operate at a certain wavelength. For example, at a wavelength of 0.95 μm.

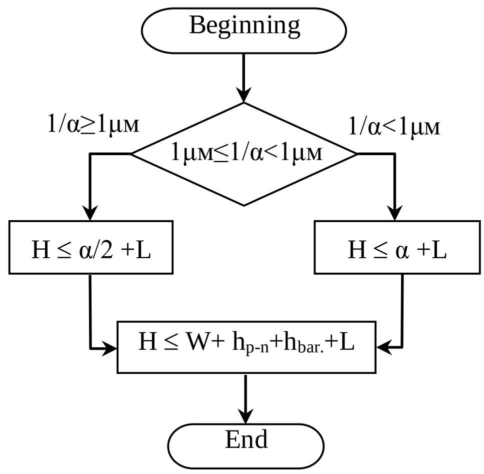

Fig. 2. Algorithm for calculating the design of a photodiode with high sensitivity in the near-infrared region of the spectrum

To meet this requirement, it can be manufactured on a silicon substrate of p-type conductivity with a resistivity of at least 10 kO•cm, orientation (111) with a lifetime of non-main carriers (200-2000) μsec. The thickness of the substrate should be no more than 1 mm. The depth of the p-n junction can be 3 - 5 μm. A protective layer of silicon oxide about 150 nm thick must be formed above the PFC. On the reverse of the silicon substrate to reduce the resistance at the metallization - silicon boundary, it is necessary to create a region of p+ - type conductivity with a depth of up to 1 μm. Through the window in the protective layer (4) a contact (5) of gold with a thickness of about 0.7 μm is formed. The thickness of the metallization layer on the reverse side (7) should be in the range of 0.5 - 1 μm.

Technological processes of manufacturing the proposed photodiode may be similar to the processes used in the formation of planar p-i-n photodiodes based on silicon.

Results and Discussion

The proposed calculation was used to assess the sensitivity of the photodiode type PD-309 [1]. The operating voltage and, accordingly, the width of the SCR (space charge region) W, were chosen taking into account the absorption depth of the operating wavelength of 0.9 μm. The calculation shows that the current monochromatic sensitivity of such a photodiode can be

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increased to 0.57 A/W in contrast to the declared sensitivity in [21] 0.5 A/W.

Technological processes of manufacturing the proposed photodiode can be similar to the processes used in the formation of silicon-based planar p-i-n photodiodes. Such processes are widely used serially in microelectron-rom production. Namely, the p-n junction can be created using planar technology based on phosphorus diffusion.

The process of diffusion in the planar technology of manufacturing semiconductor devices is decisive. In our case, phosphorus diffusion was carried out in two stages from solid sources of phosphorus. To obtain a high value of sensitivity, it is necessary to achieve an optimal concentration of minor charge carriers. It was determined by monitoring the surface resistance of silicon wafers after phosphorus diffusion.

A region of p+ - type conductivity with a depth of up to 1 μm on the reverse side of the silicon substrate is created using boron diffusion.

To check the validity of the proposed calculation and technology, a test batch of 10 photodiodes was manufactured. The design of the created photodiode was studied together with the serial photodiode FD-309. The batch of serial photodiodes also consisted of 10 pcs.

In particular, the spectral characteristics of the sensitivity of both types of photodiodes S(λ), their current impulse sensitivity Siλ, the rise time of the transient characteristic (photoresponse) and the capacitive characteristics of the photodiodes were measured and investigated. As a rule, the value of the pulse monochromatic sensitivity of a photodiode is smaller than its current monochromatic sensitivity, therefore, to evaluate both values, only one of them can be studied, namely, the pulse monochromatc sensitiviity.

The spectral characteristics of the sensitivity of photodiodes S(λ) and their impulse sensitivity were studied according to standard methods with the following clarifications:

- displacement on the photodiode 27 V;
- load resistor in the circuit of the photosensitive element 10 kΩ ± 1 %;
- modulation frequency (1 ± 0.2) kHz;
- power of optical radiation with a wavelength of 0.95 μm 10^{-4} - 10^{-6} W;
- duration of pulses 0.1 - 1.0 μs.

Limits of permissible relative measurement error S(λ) do not exceed ± 10 %.

The results of the study are shown in Figure 3 in the form of averaged values obtained on batches of 10 photodiodes. each In fig. 3, it can be seen that the current pulse sensitivity of the created photodiode is on average 0.55 A/W, and that of the serial one is 0.5 A/W. The difference is 0.05 A/W, or 10% of the average sensitivity of service photodiodes of the FD - 309 type and 0.07 A/W of the theoretically calculated value. The difference between the obtained sensitivity values of serial and newly created photodiodes is due to the fact that the design of the newly created photodiode is based on the fact that the thickness of the semiconductor substrate of the photodiode H, the diffusion length of minor charge carriers L, the depth of the barrier region hbar, the depth the occurrence of the h_{p-n} p-n junction and the width of the SCR (area of space charge) correspond to the system of inequalities (3). More precisely, the dimensions of the specified quantities and their ratio determine the optimal volume for collecting photogenerated charge carriers. Such optimization eats an additional 10% of sensitivity.

The difference between the obtained sensitivity values of the newly created photodiodes and the theoretical values is explained by the increase in the defectiveness of the photodiode structure during thermal and chemical operations for its creation.

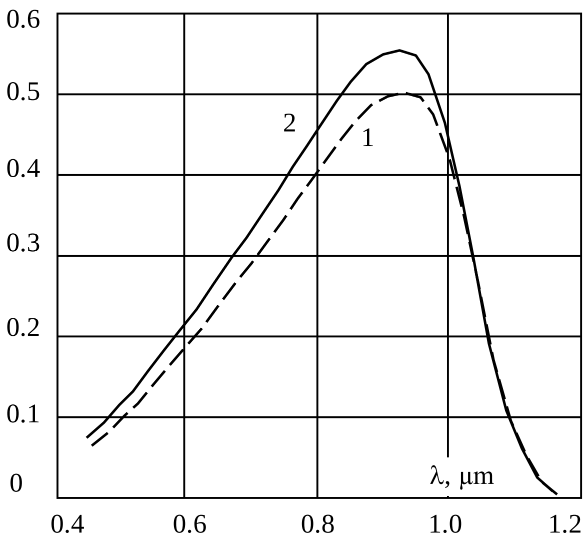

Fig. 3. Averaged spectral characteristics of current monochromatic sensitivity of serial photodiodes FD-309 (1) and created photodiodes (2)

In general, the spectral range of sensitivity of the newly created photodiodes is 0.4 - 1.1 μm. Which corresponds to the sensitivity range of serial photodiodes of the FD - 309 type.

A comparative study of the rise time of serial and newly created photodiodes was also carried out according to the standard method with refinements similar to the refinements given for the measurement of pulsed monochromatic sensitivity and spectrl sensitivity. At the same time, the duration of the pulses was set to 100 ns so that it was possible to reliably see the photoresponse of the photodiode at the level of 10 ns or more.

The limits of the permissible relative error of measurement of the rise time did not exceed ± 15%.

The results of the study are shown in Figure 4 in the form of superimposed typical oscillograms of the rise time (photoresponse) of the created and serial photodiodes.

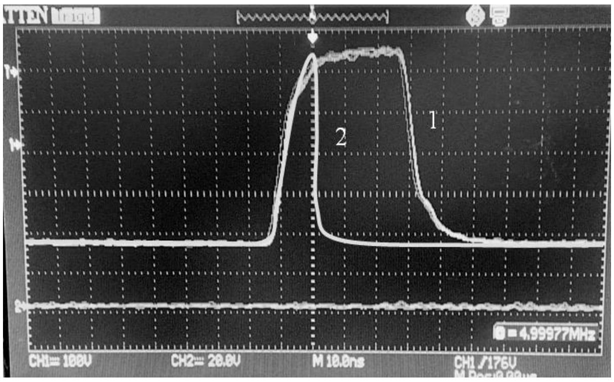

Fig. 4. Typical oscillograms of series (1) and created (2) and photodiodes

From fig. 4, it can be seen that the rise time of the created photodiode from illumination by optical radiation with a wavelength of 0.95 μm with a power of 10^{-4} - 10^{-6} W is about 10 ns, in contrast to a series photodiode, in which this parameter, measured under the same conditions, is at the level of about 50 ns. As can be seen from the measurement results, the obtained value is approximately five times smaller than the rise time of a series photodiode.

According to calculations, the rise time of the proposed photodiodes should be even shorter. But it was an average of 10 ns. Such a result can be explained in the same way as the result obtained when measuring the sensitivity, namely, the increase in the defectiveness of the photodiode structure during thermal and chemical operations for its creation.

This conclusion is confirmed by the fact that in terms of pulse current sensitivity, the newly created photodiode is better than the serial one, but the obtained value is also lower than expected.

The capacity of newly created and serial photodiodes was investigated.

Capacity measurements were carried out according to standard methods with the following clarifications:

- displacement on the photodiode 27 V;

- load resistor in the circuit of the photosensitive element 10 kΩ ± 1 %;

- measurement is made at a frequency of 100 kHz ± 20 %;

- the amount of alternating voltage supplied to the photodiode did not exceed 1 $1 \cdot 10^{-3}$ V;

- the error of capacity measurements is no more than ± 5 %.

The results of the study are shown in Figure 5 in the form of typical averaged dependences of created (2) and serial (1) photodiodes.

Figure 5 shows that the capacitance of the created photodiode is about 87-90 pF at 27 V. The capacitance of a series photodiode is about 100 pF with a similar bias. We see that the difference in capacitance between the photodiodes is small.

This is due to the fact that despite the fact that the thickness of the semiconductor substrate H of the crystals of the newly created photodiode and the series photodiode is approximately the same, the SCR in both photodiodes differs by about 10%. Which, taking into account the measurement errors of sensitivity and capacitance, coincides quite well.

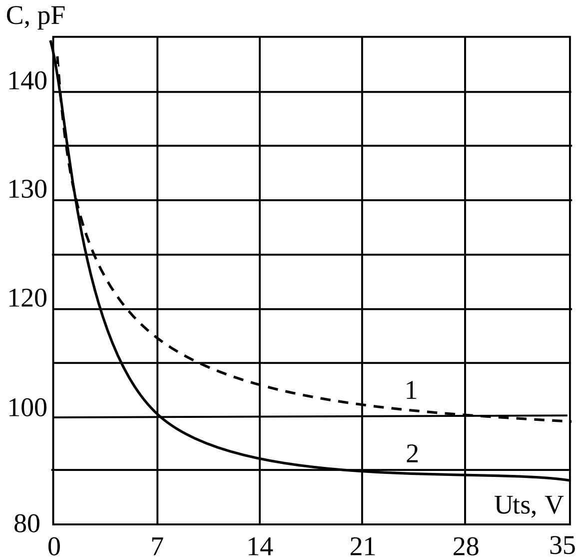

Fig. 5. Typical capacitance characteristics of serial (1) and newly created (2) photodiodes

Comparative studies of the newly reconstructed photodiode and its closest direct analogues were also carried out on the main indicator - the value of pulse or current monochromatic sensitivity ($S_{i\lambda}$) at a wavelength of 950-960 nm. Photodiodes of the type FD - 309 (CKB "Rytm", UA), S12271 (Hamamatsu, JP), BPX 65 (Sensors Inc., USA) and FD – 18 - 225 (NVP "BYT", UA) were chosen as analogs.

The results of the comparison are shown in Table 1. The comparison was also made according to the following parameters: operating wavelength (λ_p), rise time (photoresponse (ι), capacity (C) and operating voltage (U_p).

Photodiode parameters were obtained from the official websites of the above companies.

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Table 1

Results of the comparison

Name, manufacturer, country	λ_p, nm	$S_{i\lambda}$, A/W	ι, nc	C, pF	U_p, V
Newly created photodiode, UA	950	0.55	10	87	27
FD - 309 CCB "Rytm", UA	950	0.5	50	100	27
S12271 Hamamatsu, JP	960	0.4	60	10	120
BPX 65 Sensors Inc., USA	950	0.55	17	-	50

Table 1 shows that the created photodiode has better parameters compared to its direct analogue FD 309. The Japanese photodiode S12271 has a significantly lower sensitivity, but at a longer wavelength. An estimated recalculation shows that its sensitivity at a wavelength of 950 nm can reach a little more than 0.5 A/W. Its rise time is worse than the rise time of the newly created photodiode, despite the fact that the operating voltage of the analog is 120 V, which should help reduce the rise time.

The photodiode BPX 65 from the company Sensors Inc., USA, shows the same sensitivity value as that of the newly created photodiode and a close value of the rise time, but at almost twice the operating voltage. It should be noted that analogs have values of current monochromatic sensitivity, which, as mentioned above, is greater than impulse sensitivity. Therefore, despite the approximate identity of the characteristics of the newly created photodiode and its analogs, its pulse sensitivity is higher than that of analogs.

Conclusions

A model and algorithm for creating a highly sensitive silicon photodiode in the near-infrared region of the spectrum was developed, taking into account the difference in the concentration of charge carriers in the doped region and the region of intrinsic conductivity. Also, during the development of the algorithm, the influence of the absorption depth of optical radiation on the choice of the thickness of the photodiode crystal is taken into account.

Application of the FD-309 photodiode modification algorithm showed that its current monochromatic sensitivity at a wavelength of 0.95 μm can be increased from 0.5 A/W to 0.57 A/W. In the experiment, it was possible to obtain 0.55 A/W.

Future research can be devoted to the improvement of the created photodiode in aim to increase its sensitivity by optimizing the manufacturing technology for further practical application. In particular, in medical and biological research to study the dynamics of energy processes in cellular structures, as well as in light engineering research when measuring the brightness of the road surface.

Contribution of the authors: formulation of the problem statement, review and editing of the main text, assistance in creating the device and writing formulas - **Yuri Dobrovolsky**; creating, editing the main text and describing the design characteristics of the device. Final editing of the entire text according to the rules - **Yuri Sorokatyi**. All authors have read and agreed to the published version of the manuscript.

References (GOST 7.1:2006)

1. Rogalski, A. Infrared and terahertz detectors [Text] / A. Rogalski. – Boca Raton: CRC Press, 3rd ed., 2019. – 1066 p. DOI: 10.1201/b21951.

2. Low-noise and large-linear-dynamic-range photodetectors based on hybrid-perovskite thin-single-crystal [Text] / C. Bao, Z. Chen, Y. Fang, H. Wei, Y. Deng, X. Xiao, L. Li, J. Huang // Advanced materials. – 2017. – Vol. 29, Iss. 39. – P. 1–7. DOI: 10.1002/adma.201703209.

3. Ultrafast and broadband photodetectors based on a perovskite/organic bulk heterojunction for large-dynamic-range imaging [Text] / C. Li, H. Wang, F. Wang, T. Li, M. Xu, H. Wang, Z. Wang, X. Zhan, W. Hu, L. Shen // Light, science & applications. – 2020. – Vol. 9. – Article No. 31. – P. 1–8. DOI: 10.1038/s41377-020-0264-5.

4. Optical and electronic properties of femtosecond laser-induced sulfur-hyperdoped silicon N+/P photodiodes [Text] / T. Zhang, B. Liu, W. Ahmad, Y. Xuan, X. Ying, Z. Liu, Z. Chen, S. Li // Nanoscale research letters. – 2017. – Vol. 12. – Article No. 522. – P. 1–4. DOI: 10.1186/s11671-017-2287-2.

5. Sipauba Carvalho da Silva, Y. R. A highly robust silicon ultraviolet selective radiation sensor using differential spectral response method [Text] / Y. R. Sipauba Carvalho da Silva, R. Kuroda, S. Sugawa // Sensors (Basel). – 2019. – Vol. 19, No. 12. – P. 1–14. DOI: 10.3390/s19122755.

6. Ultra-high photoresponse with superiorly sensitive metal-insulator-semiconductor (MIS) structured diodes for UV photodetector application [Text] / R. Marnadu, J. Chandrasekaran, S. Maruthamuthu, V. Balasubramani, P. Vivek, R. Suresh // Applied surface science. – 2019. – Vol. 480. – P. 308–322. DOI: 10.1016/j.apsusc.2019.02.214.

7. Guo, F. Fullerene photodetectors with a linear dynamic range of 90 dB enabled by a cross-linkable buffer layer [Text] / F. Guo, Z. Xiao, J. Huang // Advanced Optical Materials. – 2013. – Vol. 1, Iss. 4. – P. 289–294. DOI: 10.1002/adom.201200071.

8. Extraordinary linear dynamic range in laser-defined functionalized graphene photodetectors [Text] / A. De Sanctis, G. F. Jones, D. J. Wehenkel, F. Bezares, *F. H. L. Koppens, M. F. Craciun, S. Russo // Science advances. – 2017. – Vol. 3, Iss. 5. – P. 1–8. DOI: 10.1126/sciadv.1602617.*

9. p-i-n photodiode based on silicon with short rise time [Text] / Yu. G. Dobrovolsky, O. P. Andreeva, M. S. Gavrilyak, L. J. Pidkamin, G. V. Prokhorov // Journal of nano- and electronic physics. – 2018. – Vol. 10, No 4. – P. 04019-1–04019-5. DOI: 10.21272/jnep.10(4).04019.

10. Photodiode based on the epitaxial phosphide gallium with increased sensitivity at a wavelength of 254 nm [Text] / Y. Dobrovolsky, V. M. Lipka, V. V. Strebezhev, Y. O. Sorokatyi, M. O. Sorokatyi, O. P. Andreeva // Informatyka, automatyka, pomiary w gospodarce i ochronie środowiska. – 2020. – Vol. 10, No. 1. – P. 36–39. DOI: 10.35784/iapgos.910.

11. Danilyuk, A. I. Estimation of frequency characteristics of photodiode determined by motion of charge carriers in the space-charge region [Text] / A. I. Danilyuk, Yu. G. Dobrovolskiy // Semiconductor physics, quantum electronics & optoelectronics. – 2006. – Vol. 9, No. 3. – P. 40–43. Available at: http://journal-spqeo.org.ua/n3_2006/v9n3-p040-043.pdf. –12.05.2022.

12. Clarifying coverages on the basis of tapes SnO_2, SiO_2, Si_3N_4 for photodiodes of ultraviolet and visible range [Text] / Yu. G. Dobrovolsciy, V. L. Perevertaylo, B. G. Shabashcevich, L. J. Pidkamin // Proceedings of the SPIE: Ninth international conference on correlation optics, Chernivsti, 31 dec. 2009. – 2009. – Vol. 7388. – P. 738815-1– 1738815-6. DOI: 10.1117/12.855112.

13. Structural parameters and polarization properties of TiN thin films prepared by reactive magnetron sputtering [Text] / M. M. Solovan, V. V. Brus, L. J. Pidkamin, P. D. Maryanchuk, Y. G. Dobrovolsky // Proceedings of the SPIE: Twelfth international conference on correlation optics, Chernivsti, 30 nov. 2015. – Vol. 9809 – 2015. – P. 980910-1–980910-8. DOI: 10.1117/12.2228981.

14. Малышев, С. А. Двумерное моделирование p−i−n-фотодиодов большой площади на основе InGaAs/InP [Текст] / С. А. Малышев, А. Л. Чиж, Ю. Г. Василевский // Физика и техника полупроводников. – 2006. – Т. 40, Вып. 9. – С. 1144–1149. – Режим доступу: http://elibrary.lt/resursai/Uzsienio%20leidiniai/ioffe/ftp/2006/09/ftp4009_23.pdf. – 12.05.2022.

15. Моделирование конструкции лавинных фотодиодов с охранными областями для регистрации маломощных световых потоков [Текст] / Н. Н. Корытко, В. Б. Залесский, В. С. Малышев, В. В. Хатько // Приборы и методы измерений. – 2011. – № 1 (2). – С. 32–39. DOI: 10.21122/2220-9506-2011-0-1-19-22.

16. Synthesis of the optimal algorithm and structure of contactless optical device for estimating the parameters of statistically uneven surfaces [Text] / O. Shmatko, V. Volosyuk, S. Zhyla, V. Pavlikov, N. Ruzhentsev, E. Tserne, A. Popov, I. Ostroumov, N. Kuzmenko, K. Dergachov, O. Sushchenko, Y. Averyanova, M. Zaliskyi, O. Solomentsev, O. Havrylenko, B. Kuznetsov, T. Nikitina // Radioelectronic and computer systems. – 2021. – No. 4. – P. 199–213. DOI: 10.32620/reks.2021.4.16.

17. Modeling of vehicle movement in computer information-control systems [Text] / V. Moiseenko, O. Golovko, V. Butenko, K. Trubchaninova // Radioelectronic and computer systems. – 2022. – No. 1. – P. 36–49. DOI:10.32620/reks.2022.1.03.

18. Comparative study of afterpulsing behavior and models in single photon counting avalanche photo diode detectors [Text] / A. W Ziarkash, S. K. Joshi, M. Stipčević, R. Ursin // Scientific reports. – 2018. – Vol. 8. – Article No. 5076. – P. 1–8. DOI: 10.1038/s41598-018-23398-z.

19. Modeling of frequency-dependent negative differential capacitance in InGaAs/InP photodiode [Text] / Y. Wang, J. Chen, J. Xu, X. Li // Infrared physics & technology. – 2018. – Vol. 89. – P. 41–45. DOI: 10.1016/j.infrared.2017.12.005.

20. Khan, U. Dynamic capacitance variations due to barrier modulation in pinned photodiode of CMOS image sensor [Text] / U. Khan, M. Sarkar // IEEE transactions on electron devices. – 2019. – Vol. 66, Iss. 12. – P. 5202–5208. DOI: 10.1109/TED.2019.2947774.

21. Alaibakhsh, H. A general compact pinned photodiode model capable of miniature PPD modeling [Text] / H. Alaibakhsh, M. A. Karami // IEEE transactions on electron devices. – 2021. – Vol. 68, – Iss. 6. – P. 2785–2790. DOI: 10.1109/TED.2021.3072023.

References (BSI)

1. Rogalski, A. *Infrared and terahertz detectors*. Boca Raton, CRC Press Publ. 3rd ed., 2019. 1066 p. DOI: 10.1201/b21951.

2. Bao, C., Chen, Z., Fang, Y., Wei, H., Deng, Y., Xiao, X., Li, L., Huang, J. Low-noise and large-linear-dynamic-range photodetectors based on hybrid-perovskite thin-single-crystals. *Advanced materials*, 2017, vol. 29, iss. 39, pp. 1–7. DOI: 10.1002/adma.201703209.

3. Li, C. , Wang, H. , Wang, F. , Li, T., Xu, M., Wang, H., Wang, Z., Zhan, X., Hu, W, Shen, L. Ultrafast and broadband photodetectors based on a perovskite/organic bulk heterojunction for large-dynamic-range imaging. *Light, science & applications* 2020, vol. 9, article no. 31, pp. 1–8. DOI: 10.1038/s41377-020-0264-57.

4. Zhang, T., Liu, B., Ahmad, W., Xuan, Y., Ying, X., Liu, Z., Chen, Z., Li, S. Optical and electronic properties of femtosecond laser-induced sulfur-hyperdoped silicon N^+/P photodiodes. *Nanoscale research letters*, 2017, vol. 12, article no. 522, pp. 1–4. DOI: 10.1186/s11671-017-2287-2.

5. Sipauba Carvalho da Silva, Y. R., Kuroda, R., Sugawa, S. Highly robust silicon ultraviolet selective radiation sensor using differential spectral response method. *Sensors*, 2019, vol. 19, no. 12, pp. 1–14. DOI: 10.3390/s19122755.

6. Marnadu, R., Chandrasekaran, J., Maruthamuthu, S., Balasubramani, V., Vivek, P., Suresh, R. Ultra-high photoresponse with superiorly sensitive metal-insulator-semiconductor (MIS) structured diodes for UV

ISSN 1814-4225 (print)
ISSN 2663-2012 (online)

photodetector application. *Applied Surface Science*, 2019, vol. 480, pp. 308–322. DOI: 10.1016/j.apsusc.2019.02.214.

7. Guo, F., Xiao, Z., Huang, J. Fullerene photodetectors with a linear dynamic range of 90 dB enabled by a cross-linkable buffer layer. *Advanced Optical Materials,* 2013, vol. 1, iss. 4, pp. 289–294. DOI: 10.1002/adom.201200071.

8. De Sanctis, A., Jones, G. F., Wehenkel, D. J., Bezares, F., Koppens, F. H. L., Craciun, M. F., Russo, S. Extraordinary linear dynamic range in laser-defined functionalized graphene photodetectors. *Science Advances,* 2017, vol. 3, iss. 5, pp. 1–8. DOI: 10.1126/sciadv.1602617.

9. Dobrovolsky, Yu. G., Andreeva, O. P., Gavrilyak, M. S., Pidkamin, L. J., Prokhorov, G. V. p-i-n Photodiode Based on Silicon with Short Rise Time. *Journal of nano- and electronic physics*, 2018, vol. 10, no 4, pp. 04019-1–04019-5. DOI: 10.21272/jnep.10(4).04019.

10. Dobrovolsky, Yu. G., Lipka, V. M., Strebezhev, V. V., Sorokatyi, Yu. O., Sorokatyi, M. O., Andreeva, O. P. Photodiode on the basis of epitaxial phosphate gallium with increased sensitivity at a wavelength of 254 nm. *Informatyka, automatyka, pomiary w gospodarce i ochronie środowiska*, 2020, vol. 10, no. 1, pp. 36–39. DOI: 10.35784/iapgos.910.

11. Danilyuk, A. I., Dobrovolskiy, Yu. G. Estimation of frequency characteristics of photodiode determined by motion of charge carriers in the space-charge region. *Semiconductor physics, quantum electronics & optoelectronics,* 2006, vol. 9, no. 3. pp. 40–43. Available at: http://journal-spqeo.org.ua/n3_2006/v9n3-p040-043.pdf. (accessed 12.05.2022).

12. Dobrovolsciy, Yu. G., Perevertaylo, V. L., Shabashcevich, B. G., Pidkamin, L. J. Clarifying coverages on the basis of tapes SnO_2, SiO_2, Si_3N_4 for photodiodes of ultraviolet and visible range. *Proceedings of the SPIE. Vol. 7388: Ninth international conference on correlation optics*. Chernivsti, 2009, pp. 738815-1– 1738815-6. DOI: 10.1117/12.855112.

13. Solovan, M. M., Brus, V. V., Pidkamin, L. J.,. Maryanchuk, P. D. Structural parameters and polarization properties of TiN thin films prepared by reactive magnetron sputtering. *Proceedings of the SPIE: Twelfth international conference on correlation optics*. Chernivsti, 30 nov. 2015,vol. 9809, pp. 980910-1–980910-8. DOI: 10.1117/12.2228981.

14. Malyshev, S. A., Chizh, A. L., Vasileuski, Ju. G. Dvumernoe modelirovanie p–i–n-fotodiodov bol'shoj ploshhadi na osnove InGaAs/InP [2D modeling of large area InGaAs/InP p–i–n photodiodes]. *Fizika i tehnika poluprovodnikov – Semiconductors,* 2006, vol. 40, no. 9, pp. 1144-1149. Available at: http://elibrary.lt/resursai/Uzsienio%20leidiniai/ioffe/ftp/2006/09/ftp4009_23.pdf. (accessed 12.05.2022).

15. Korytko, N. N., Zalesskij, V. B., Malyshev, V. S., Khatko, V. V. Modelirovanie konstrukcii lavinnyh fotodiodov s ohrannymi oblastjami dlja registracii maloмoshhnyh svetovyh potokov. [Simulation of avalanche photodiode construction with guard areas] *Pribory i metody izmerenij – Devices and Methods of Measurements,* 2011, no 1 (2), pp. 32–39. DOI: 10.21122/2220-9506-2011-0-1-19-22.

16. Shmatko, O., Volosyuk, V., Zhyla, S., Pavlikov, V., Ruzhentsev, N., Tserne, E., Popov, A., Ostroumov, I., Kuzmenko, N., Dergachov, K., Sushchenko, O., Averyanova, Y., Zaliskyi, M., Solomentsev, O., Havrylenko, O., Kuznetsov, B., Nikitina, T. Synthesis of the Optimal Algorithm and Structure of Contactless Optical Device for Estimating the Parameters of Statistically Uneven Surfaces. *Radioelectronic and computer systems*, 2021, no. 4, pp. 199–213. DOI: 10.32620/reks.2021.4.16.

17. Moiseenko, V., Golovko, O., Butenko, V., Trubchaninova, K. Modeling of Vehicle Movement in Computer Information-Control Systems. *Trubchaninova Radioelectronic and Computer Systems*, 2022, no. 1, pp. 36–49. DOI: 10.32620/reks.2022.1.03.

18. Ziarkash, A. W., Joshi, S. K., Stipčević, M., Ursin R. Comparative study of afterpulsing behavior and models in single photon counting avalanche photo diode detectors. *Scientific reports*, 2018, vol. 8. article no. 5076, pp. 1–8. DOI: 10.1038/s41598-018-23398-z.

19. Wang, Y. Chen, J., Xu, J., Li, X. Modeling of frequency-dependent negative differential capacitance in InGaAs/InP photodiode. *Infrared physics & technology,* 2018, vol. 89, pp. 41–45. DOI: 10.1016/j.infrared.2017.12.005.

20. Khan, U., Sarkar, M. Dynamic Capacitance Variations Due to Barrier Modulation in Pinned Photodiode of CMOS Image Sensor. *IEEE transactions on electron devices,* 2019, vol. 66, iss. 12, pp. 5202–5208. DOI: 10.1109/TED.2019.2947774.

21. Alaibakhsh, H., Karami M. A. A general compact pinned photodiode model capable of miniature PPD modeling. *IEEE transactions on electron devices,* 2021, vol. 68, iss. 6, pp. 2785–2790. DOI: 10.1109/TED.2021.3072023.

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МОДЕЛЬ ТА АЛГОРИТМ СТВОРЕННЯ КРЕМНІЄВОГО ФОТОДІОДУ З ПІДВИЩЕНОЮ ЧУТЛИВІСТЮ У БЛИЖНІЙ ІНФРАЧЕРВОНІЙ ОБЛАСТІ СПЕКТРУ

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Чутливість фотодіода буде залежати від величини потужності випромінювання, яку він повинен зареєструвати. Характеристики фотодіода, як відомо, визначаються його конструкцією. Зокрема, характеристики використовуваного матеріалу, конфігурація електричних полів, рухливість носіїв заряду, ширина SCR (області просторового заряду) і т. д. Крім того, характеристики фотодіода визначаються зовнішніми прикладена напруга і довжина хвилі прийнятого оптичного випромінювання. У разі його поглинання тільки в ОПЗ (області просторового заряду) і на незначних відстанях навколо нього, наприклад, в p-i-n фотодіоді, його частотні характеристики будуть визначатися в основному часом прольоту генерованих носіїв заряду через ОПЗ. **Предметом є** створення алгоритму побудови фотодіода, який повинен працювати на певній довжині хвилі. Наприклад, на довжині хвилі 0,95 мкм. В якості вихідного матеріалу був обраний кремній p-типу провідності з питомим опором не менше 10 кОм • см. **Метою є** створення моделі та алгоритму розробки фотодіоду, здатного забезпечувати максимальні значення струмової монохроматичної чутливості за рахунок максимального збору фотогенерованих носіїв заряду в його об'ємі при відповідному зовнішньому зміщенні. **Завдання:** для задоволення цієї вимоги потрібно здійснити теоретичні та експериментальні дослідження. **Методи:** Технологічні процеси виготовлення запропонованого фотодіода можуть бути подібні до процесів формування планарних p-i-n фотодіодів на основі кремнію. Пропоноване технічне рішення обумовлює кореляцію між областю збору фотогенерованих носіїв заряду та областю їх генерації. Результату можна досягти, змінивши конструкцію кристала фотодіода з урахуванням отриманих теоретичнирх висновків. **Результати:** Проведено аналіз факторів, що визначають струмову монохроматичну чутливість фотодіоду. Розроблено конструкцію фотодіоду з підвищеною чутливістю у порівнянні із серійним фотодіодом типу ФД-309. **Висновки:** запропонований розрахунок використано для оцінки чутливості фотодіода. Робочу напругу і, відповідно, ширину ОПЗ (області просторового заряду) W вибирали з урахуванням глибини поглинання робочої довжини хвилі 0,95 мкм. Розрахунок показує, що поточну струмову монохроматичну чутливість такого фотодіода можна збільшити до 0,57 А/Вт на відміну від заявленої чутливості 0,5 А/Вт. Проведено порівняльні дослідження виготовленої партії створених фотодіодів та фотодіодів ФД-309, яке показало, що запропонований фотодіод дійсно володіє струмовою монохроматичною чутливістю на довжині хвилі 0,95 мкм не менше 0,55 А/Вт. При цьому його час зростання зменшено з 50 нс до 10 нс, а ємність складає 90 пФ замість 100 пФ у ФД-309.

Ключові слова: Фотодіод; кремній; довжина хвилі; монохроматичний; область просторового заряду (ОПЗ); інфрачервоний (ІЧ).

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