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METHODS OF CORRECTION OF SPECTRAL CHARACTERISTICS OF SILICON PHOTODETECTORS

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The paper investigates methods for shifting the spectral characteristics of silicon photodiodes toward longer wavelengths. It is established that with increasing the reverse bias voltage of the photodiode, the maximum spectral characteristic shifts towards longer wavelengths due to an increase in the collection coefficient of minority charge carriers, which determines the appearance of the spectral characteristic. With an increase in the lifetime of minor charge carriers and the resistivity of the photodiode base material, the maximum of its spectral characteristic also shifts towards longer wavelengths. Increasing the n^+-junction depth of the photodiode reduces the effect of background short-wave radiation on the useful signal of the photodiode. Silicon cut-off adsorption light filters have been proposed that eliminate the influence of background radiation with a wavelength of less than 800 nm on the photodiode signal and have a transmittance of about 75% at a wavelength of 1064 nm.

Keywords: *Silicon; Photodetector; Sensitivity; Spectral Characteristics; Optical Transmission*
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The main task of photodetectors is to detect monochromatic laser radiation. Therefore, photodetectors designed for such applications must demonstrate increased sensitivity at a specific wavelength (λ). The spectral sensitivity characteristic of a photodiode, $S(\lambda)$, describes how its monochromatic sensitivity varies with wavelength. This knowledge is important not only for evaluating the operation of a photodetector with coherent radiation sources, but also for analyzing the operation with incoherent sources whose spectral composition is known [1].

Ensuring a given type of the photodetector's spectral response is usually realized by using a semiconductor material with different band gaps E_g [2], since it is the band gap that determines in which part of the spectrum the semiconductor has the greatest sensitivity to photogeneration of charge carriers (1):

$$\lambda = \frac{hc}{E_g} \tag{1}$$

where h is the Planck constant, c is the speed of light.

To shift the spectral characteristic towards longer wavelengths, materials with higher E_g are used. For example, silicon photodiodes are used for the visible and near-infrared spectrum. For the infrared spectrum, materials based on GaAs (E_g = 1.42 eV) [3, 4], Ge (E_g = 0.66 eV) [5, 6], or InP (E_g = 1.34 eV) [7] are used. The use of heterostructures (with different materials) can change the width of the bandgap in a wide range, which allows controlling the spectral sensitivity of the photodiode [8, 9]. For this purpose, multilayer structures are used, where different layers have different E_g.

When the photodiode is heated, the width of the bandgap changes, which can lead to a shift in the spectral maximum toward longer wavelengths. However, this method is less controllable and often has a negative impact on the characteristics of the photodiode [10].

An urgent task of modern photoelectronics is the development and manufacture of efficient and highly sensitive photodetectors for detecting YAG lasers (λ = 1064 nm) [11, 12]. Silicon is the main material for this task, but under normal conditions, Si-based photodiodes have a λ_{max}=800-900 nm [6, 10]. Accordingly, there is a need to develop methods for shifting the spectral maximum of silicon photodiodes (PD) towards longer wavelengths.

One of the effective methods of shifting the spectral characteristics of the PD is the use of light filters, in particular, interference bandpass filters or adsorption cutoff filters. High-quality interference bandpass filters are characterized by a high transmittance and can ($T \geq 90\%$) isolate narrow spectral regions (up to 15-20 Å) [13, 14]. Striking examples of light filters for λ=1064 nm on the market are FLH051064-3 [15], or FLH1064-3 (THORLABS) with $T > 90\%$ (at λ=1064 nm) and a bandwidth at λ=1041-1087 nm [16]; 20CGA1000 (NEWPORT) with a bandwidth of λ>1000 nm and $T \geq 90\%$ [17]. The disadvantage of interference optical filters is the dependence of the position of the transmission bands on the angle of incidence of light, cost, complexity of manufacturing, the need for special equipment, expensive materials for creating layers, and calculation programs.

Adsorption filters are the most common class of optical filters that have spectral selectivity due to unequal absorption of light in different wavelength ranges. These are usually different semiconductor materials or types of glass [13]. Silicon adsorption filters, with or without anti-reflective coating, are a common choice for reducing the effect of short-wave

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radiation on the useful signal of IR photodiodes [18]. In [19], we proposed silicon adsorption light filters with an anti-reflective coating, with a bandwidth of λ>900 nm and $T \leq$60-65% (at λ=1064 nm). The relatively low transmittance of the filters is due to the need to manufacture samples with a thickness that provides adequate mechanical strength.

A review of the sources shows that the study of the possibilities of shifting the spectral characteristics of silicon PDs towards longer wavelengths is an urgent scientific and technical task, which is the purpose of this work.

EXPERIMENTAL

The research was carried out in the manufacture of silicon 4Q *p-i-n* PDs for operation at wavelength λ = 1064 nm (Fig. 1a). PDs were made on the basis of single-crystal *p*-type FZ-Si with [111] orientation. The samples were made by diffusion-planar technology according to the technological regimes given in [20]. Silicon with different resistivity of ρ = 12-22 kΩ·cm and different lifetime of non-basic charge carriers of τ=1-2 ms was used.

The PDs with different depths of the *p-n*-junction, which was adjusted by the duration of phosphorus deposition, were studied. Samples with x_{n+-p} = 3.5-6 µm were fabricated. The spectral characteristics of sensitivity at different bias voltages were studied in the PDs made of different base materials and with different x_{n+-p}.

The possibility of increasing the transmittance of silicon light filters in combination with silicon photodiodes (PDs) is investigated. The best option for increasing the transmittance of a light filter is to reduce its thickness, but this significantly reduces its mechanical strength. We proposed to thin the filter only in the zones that are projections of responsive elements, and to leave the periphery of the light filter of sufficient thickness to ensure proper mechanical strength (Fig. 1b). This was done by etching the silicon by chemical-dynamic polishing in a solution of HNO_3:HF:CH_3COOH with a masking gold coating (Fig. 2). Gold was chosen as a masking coating because photoresists are not sufficiently chemically resistant to aggressive etching agents during prolonged etching. Since gold has poor adhesion to silicon, an adhesive sublayer of chromium was formed [21]. The metallization was applied by thermal evaporation in a vacuum. The thickness of the gold layer reached 400-500 nm, and that of chromium 30-70 nm. The etching was carried out in 3 stages of 10 min each. The thickness of the silicon base of the light filter reached 250-300 µm, and the projections of the responsive elements after chemical-dynamic polishing reached 70 µm. After CDP and metallization etching, the silicon substrates were oxidized in a dry oxygen atmosphere according to the method given in [22]. The film of SiO_2 thickness reached 180-190 nm, which corresponds to the condition of minimum reflection of radiation with λ = 1064 nm [23]. The proposed filters in combination with the PD were compared with flat silicon filters of greater thickness.

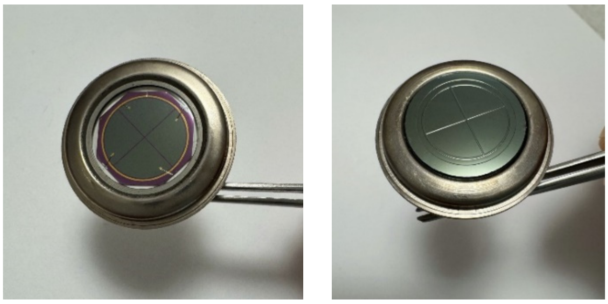
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Figure 1. Images of a photodiode
(a) – without a light filter and (b) – with the proposed filter

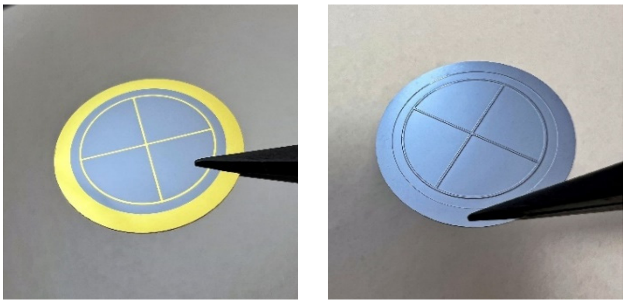
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Figure 2. Images of a filter with a masking coating
(a) – before etching and (b) – a light filter with etched projections of responsive elements

Investigation of the transmission spectra were performed using SF-2000 spectrophotometers at room temperature. The spectral characteristics of responsivity were measured using the KSVU-23 automated spectral complex.

RESULTS OF THE RESEARCH AND THEIR DISCUSSION

A) Study of the dark currents

It was found that with an increase in the reverse bias voltage, the maximum of the spectral characteristic shifts towards longer wavelengths Fig. 3. This is due to an increase in the size of the space charge region W_i (2) [24], with an increase in which the collection coefficient of photogenerated charge carriers increases (γ) (3) [25], and the appearance and maximum spectral characteristic of the PD is primarily determined by the collection coefficient (4) [6].

$$W_i = \left(\frac{2\varepsilon\varepsilon_0\,(\phi_c - U_{bias})}{eN_A}\right)^{\frac{1}{2}}. \tag{2}$$

ε, ε_0 are dielectric constants for silicon and vacuum, respectively; φ_c is contact potential difference, e is the electron charge, N_A is concentration of acceptors, U_{bias} is bias voltage.

$$\gamma = 1 - e^{-\alpha(W_i + L_n)}, \tag{3}$$

α is absorption coefficient, L_n is diffusion length of minor charge carriers.

$$S_\lambda = (1 - R)TQ\sum\gamma\frac{\lambda}{1.24} \tag{4}$$

where T is the transmission coefficient of the input window or optical filter, Q is the quantum output of the internal photoeffect, R is the reflection coefficient.

It has also been found that with an increase in the resistivity and lifetime of minority charge carriers of silicon at the same bias voltage, the maximum of the spectral characteristic also shifts towards longer wavelengths (Fig. 4). This phenomenon is also related to the charge carrier collection coefficient, since at the same bias voltage, the PD with a higher resistivity will have a larger width of the space charge region. Note that an increase in the lifetime of charge carriers also increases the collection coefficient due to an increase in the diffusion length and an increase in the collection area of photogenerated charge carriers [26].

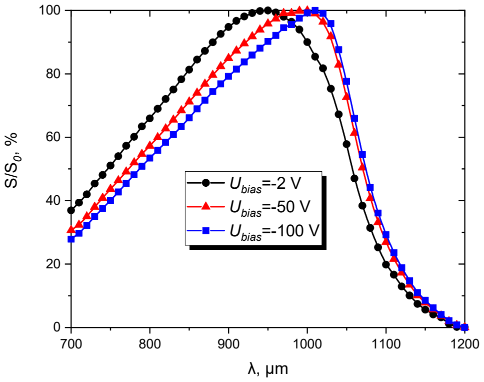

Figure 3. Relative spectral characteristic of the PD at different U_{bias}

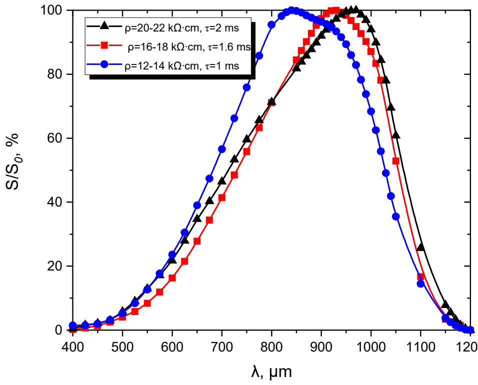

Figure 4. Relative spectral characteristic of the PD with different ρ and τ of silicon at U_{bias}=-2 V

It should be noted that the electrophysical characteristics of silicon can degrade during technological operations, in particular thermal ones. This degradation is possible due to poor-quality chemical treatments, the introduction of uncontrolled impurities (thermodonors) from quartz tooling, the use of carrier gases or deionized water of insufficient quality. This degradation can occur to varying degrees in different batches, which will result in different maximum spectral characteristics when using the same base material [27-29].

It was found that with an increase in the depth of the n^+-p junction, the effect of short-wave background radiation on the useful signal of the photodiode decreases, i.e., the slope of the spectral response changes (Fig. 5). The decrease in the sensitivity of the photodiode to shortwave radiation with increasing x_{n+-p} is due to the fact that in *p-i-n* PDs, the photogeneration of charge carriers that reach the *p-n* junction occurs in the *i*-region, the charge carriers generated in the n^+-layer recombine before reaching the *p-n* junction. Accordingly, the generation of non-equilibrium charge carriers in the high-resistance region of the PD occurs only by those wavelengths that penetrate the *i*-region. Thus, radiation with λ = 0.95 μm is absorbed in Si at a depth of about 63 μm, and with λ = 0.7 is absorbed in Si at a depth of about 4.33 μm [30]. Accordingly, by increasing the depth of the n^+-p junction, the influence of short-wave background radiation on the photodetector signal can be excluded.

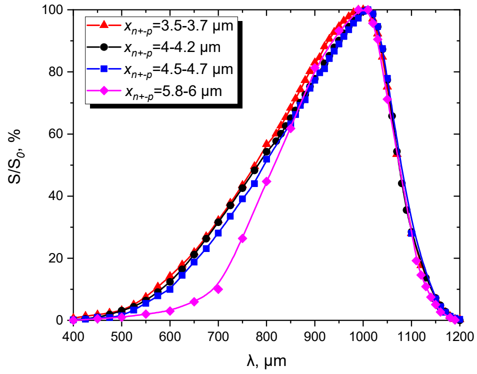

Figure 5. Relative spectral characteristic of the PD with different x_{n+-p}

An increase in the depth of the phosphorus impurity is possible with an increase in the duration of the phosphorus driving-in operation, but its significant duration is negative, since an increase in the total duration of high-temperature thermal operations provokes an increase in the degree of degradation of the electrophysical characteristics of silicon and the formation of inversion layers at the Si-SiO$_2$ interface, which negatively affects the final parameters of the products [28, 29, 31].

The transmission spectra of silicon light filters of different thicknesses were obtained (Fig. 6). It was found that as the thickness of the filter increases, its transmittance decreases according to the Bouguer-Lambert Beer law [32]. Thus, a filter with a thickness of *d*=70 μm has a transmittance at λ=1064 nm of about *T*=75%, *d*=170 μm - *T*=66%, *d*=240 μm - *T*=62%, *d*=280 μm - *T*=57%. Also, from Fig. 6, it can be seen that with a decrease in the thickness of the filter, the edge of its absorption shifts towards shorter wavelengths.

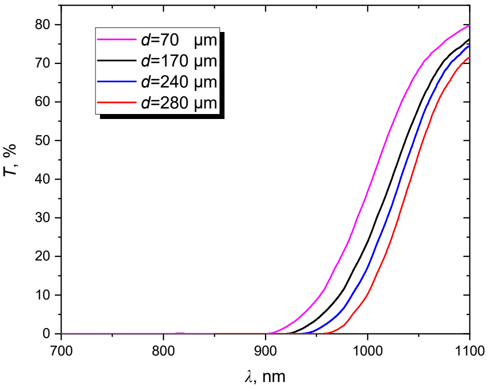

Figure 6. Transmission spectrum of light filters

We also obtained the spectral characteristics of the photodetectors with light filters (Fig. 7) and found that with an increase in the filter thickness, the maximum spectral response of the photodetector shifts towards longer wavelengths, and the short-wave edge of the photosensitivity shifts towards longer wavelengths. Thus, a photodetector with a filter with *d* = 430 μm becomes sensitive at λ≥ 950 μm, and has a maximum sensitivity at λ_m = 1060 nm, but has a low sensitivity value due to the high thickness of the filter. A light filter with *d*=70 μm becomes sensitive at λ≥800 μm, and has a maximum sensitivity at λ=1030 nm, but the absolute value of its sensitivity is almost the same as the PD without a light filter. Note that in the PD without a filter, λ_m=1020 nm, so the filter with *d*=70 shifts λ_m by only 10 nm.

It is worth noting that with an increase in the bias voltage, the spectral characteristic of the PD with a filter also shifts towards longer wavelengths (Fig. 8).

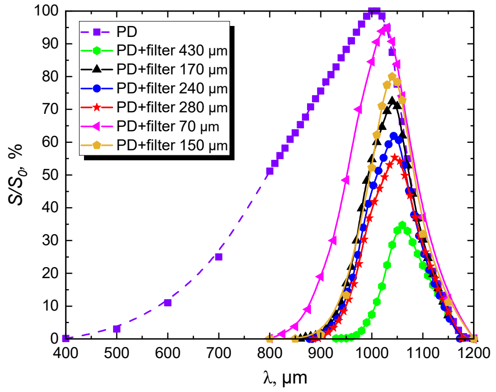

Figure 7. Relative spectral characteristic of the PD with filters of various thicknesses at U_{bais}=-120 V

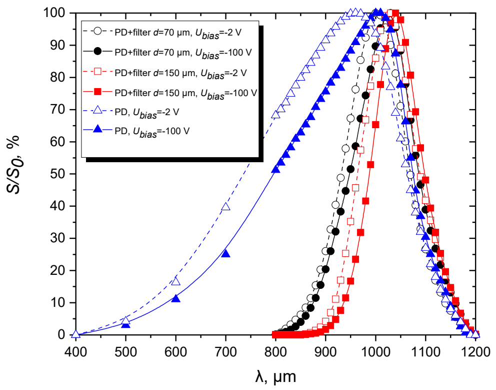

Figure 8. Relative spectral characteristic of the PD with filters of various thicknesses at U_{bais}=-2 V and U_{bais}=-100 V (characteristics are given to 100 %)

Increasing the thickness of the filter improves its selectivity. Optical concentrators can be used in the design of the PD to level the absorption of radiation by the filter thickness [33]. The proposed light filters are a cheap and no less effective analog of interference bandpass filters for the near-infrared region with a much simpler manufacturing technology.

CONCLUSIONS

The methods of correction of the spectral characteristics of silicon photodiodes, in particular, the methods of its shift towards longer wavelengths, are investigated. The following conclusions have been drawn:

1. With an increase in the reverse bias voltage of the photodiode, the maximum spectral characteristic shifts towards longer wavelengths
2. With an increase in the resistivity and diffusion length of minor charge carriers of silicon, the maximum spectral characteristic of silicon shifts towards longer wavelengths.
3. With an increase in the depth of the n^+-*p* junction, the effect of short-wave radiation on the useful signal of the photodiode decreases due to the absorption of short wavelengths by the n^+-layer.
4. The use of silicon cut-off adsorption light filters eliminates the influence of short-wave background radiation on the photodiode signal at λ≥800 nm. Also, the proposed filters allow to shift the maximum of the spectral characteristic

towards longer wavelengths. With the increase of the filter thickness, its optical transmittance decreases but selectivity improves.

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МЕТОДИ КОРЕКЦІЇ СПЕКТРАЛЬНИХ ХАРАКТЕРИСТИК КРЕМНІЄВИХ ФОТОПРИЙМАЧІВ

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У статті досліджено методи зміщення спектральних характеристик кремнієвих фотодіодів в сторону більших довжин хвиль. Встановлено що при збільшенні напруги зворотнього зміщення фотодіода максимум його спектральної характеристики зміщується в сторону більших довжин хвиль внаслідок зростання коефіцієнта збирання неосновних носіїв заряду, який визначає вигляд спектральної характеристики. При збільшенні часу життя неосновних носіїв заряду та питомого опору базового матеріалу фотодіода максимум його спектральної характеристики також зміщається в сторону більших довжин хвиль. Збільшення глибини гетеропереходу фотодіода зменшує вплив фонового короткохвильового випромінювання на корисний сигнал фотодіода внаслідок рекомбінації фотоггенерованих носіїв заряду довжинами хиль, які поглинаються в n^+-шарі. Запропоновано кремнієві відрізаючі адсорбційні світлофільтри, які виключають вплив фонового випромінювання з довжиною хвилі менше 800 нм на сигнал фотодіода та володіють коефіцієнтом пропускання близько 75% на довжині хвилі 1064 нм.

Ключові слова: *кремній; фотоприймач; чутливість; спектральна характеристика; оптичне пропускання*