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p-i-n Photodiode Based on Silicon with Short Rise Time

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The factors that influence the rise time of the photodiode are investigated and analyzed. Using the obtained results, a photodiode based on a high-ohmic silicon of *p*-type conductivity with a minimized rise time has been developed. The proposed construction. contains a contact on the back of the crystal of a photodiode, which is not continuous, but has a hole. Such a hole is the projection of a photosensitive element on the reverse side of the crystal of a photodiode. The value of the rise time of this photodiode is no more than 9 ns compared to 37 ns in the FD-255 A analogue.

Keywords: Photodiode, Rise time, Boundary frequency, Current-generation.

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1. INTRODUCTION

Optical emission is the carrier of a huge amount of information that various branches of science use to their advantage. It creates unique opportunities for remote research of both micro- and macroobjects, which are located from us at a distance of several nanometers and hundreds of parsecs.

Modern information transmission systems are based on various methods, one of which is an optical method based on the transmission over a fiber optic cable. Modern methods of processing and transmission of information streams provide a data transfer rate with fiber up to 1.4 Tbit/s. This bandwidth, for example, is enough to transfer 44 uncompressed movies in HD quality within a second.

A receiver and a primary converter in this case is a photodiode, that has a high level of performance. As the photodiode, this concept has two reciprocal characteristics.

We are talking about the boundary frequency and the rise time of photo diodes [1].

It is clear that the performance increasing of the photodiode is based on many factors, in particular - either an increase in the boundary frequency, or a decrease in the rise time.

2. CPURPOSE OF THE STUDY

In fact, this the purpose of the investigation to create recommendations and proposals for the development of a photodiode with increased performance, or, respectively, the minimum rise time.

3. RESULTS OF THE STUDY

The rise time is the most important dynamic characteristic of the photodetector. It is defined as the time required by the output signal to increase from a level of 0.1 to 0.9 from the steady-state maximum value, provided that rectangular light pulses of long duration that are applied to the input.

This time depends on the geometry of the photodiode, the material, the strength of the electric field in the weakly doped region, and the temperature. As the frequency of modulation of the input optical pulses increases, the maximum value of the photocurrent decreases. The boundary frequency is defined as the modulation frequency at which the current sensitivity is 0.707 of the current sensitivity value at low modulation frequencies. Different photodetectors can differ greatly in speed. The fastest are *p-i-n* photodiodes.

Thus, to work in the transmission system of information flows in the optical range of the spectrum using fiber optic fiber cable, an appropriate photodiode with high performance rate is needed.

Actually, to estimate the performance rate of a photodiode or its rise time (on the other hand, the rate of generation of non-main carriers of current by the flow of optical emission and their advance to the *p-n* junction) can be obtained by estimating the photocurrent value of a photodiode for a simple case when the radiation is absorbed in the *n*-domain of the *p-n* junction. In this case the intensity of the light is constant in the thickness $\alpha\omega << 1$, where ω – is the thickness of the base.

With reverse bias, the process of transfer of light-generated carriers does not differ from the transfer of equilibrium charge carriers in the *n*-base. To determine the photocurrent, we use the formula for the reverse current of the *p-n* junction (I_{SatC}), which for the case $p_p >> n$ looks like

$$I_{SatC} = e \times S \times L_P \times p_p / t_p,$$

This is the current of nonequilibrium charge carriers generated at the rate p_p/τ_p in the base layer, width equal to the length of the non-core carriers (holes) L_p. By analogy, the photocurrent (I_{Ph}) will be

$$I_{Ph} = e \times S \times (DP / t_p) \times w, \quad (1)$$

where ($\Delta P/\tau_p$) – the rate of light-generating non-core current carriers;
S – the area of light receiving surface;
ΔP – the concentration of light-generated holes.
The relationship is valid $\omega << L_p$.

$$\Delta P = \eta\alpha\tau_p \Phi, \quad (2)$$

where Φ – light flux,

η – quantum photoelectric effect ,
α – absorption coefficient.

Substituting expression for P in (2) we obtain

$$I_{Ph} = e \cdot \alpha \cdot \omega \eta \cdot S \cdot \Phi = e \cdot C \cdot \eta \cdot S \cdot \Phi, \qquad (3)$$

where $C = \alpha \cdot \omega$ – dimensionless coefficient characterizing the proportion of radiation, absorbed in the base.

Formula (3) remains valid for a real case when the intensity of light decreases by exponential law. If the expression for the photocurrent (3) is taken per unit area and the reflection losses from the illuminated surface are taken into account, then:

$$I = (1-R)Q\square\eta\square e,$$

Thus, it is seen that the value of the photocurrent according to formulas (1) and (2) is determined by the rate of generation of electron-hole pairs under the action of optical radiation.

For an "ideal" inertial receiver, the dependence of the amplitude of the output signal from the modulation frequency looks like:

$$U_{\text{OV}}(\omega) = \frac{U_{OV}(0)}{\sqrt{1+(\omega\tau)^2}},$$

where $U_{OV}(0)$ = amplitude of the signal of the photodetector at the "zero" frequency, τ – constant of front rise, or the time of rise of the photodetector.

It is seen that for this case the constant time is determined from the condition $2\pi f_{гр}\tau = 1$. Or, the rise time of the photodiode is inversely proportional to its boundary frequency as:

$$\tau = 1/2\pi f_{гр.}, \qquad (4)$$

Since the mechanisms of generating non-core charge carriers in a photodiode may be several ones, the value of the rise time of its transient characteristic may be different. In the following investigations [2, 3] the questions of the evaluation of the frequency characteristics of the photodiode, in particular, for the case of the motion of the charge carriers inside the crystal of a semiconductor in the electric field of the space charge region x_0 (SCR), and in the case of uniform electric field tension in the crystal and the surface current generation, were considered.

It is determined that when the frequency characteristics are defined only by the time of the passage of charge carriers through the SCR in the general case, when the photo signal is modulated, the increase in current I in the external circle (the current of the photo signal) can be represented as:

$$d_x d_{x'} I = \frac{E_x(x)}{\int\limits_0^{x_0} E_x(x)dx} \cdot sin\omega\left(t - \int\limits_{x'}^{x} \frac{d\vec{x}''}{\vec{E}_{x''}(x)\bar{\mu}}\right)\frac{\partial I_0}{\partial x'}dx'dx,$$

where: $\vec{E}_x(x)$ – vector of the electric field intensity at the coordinate point x;
$\bar{\mu}_x$ – the averaged mobility of these charge carriers at the coordinate point x;
I_0 – effective (internal) amplitude of the variable component of the generated photocurrent;
dx', dx – the thickness of two elementary layers in the form of flat domains, parallel to the boundaries of the SCR within it and pass, respectively, in the vicinity of points with coordinates x' i x;

That is, the current in the external circuit depends on two functions of the coordinates: the electric field strength and the current density of the photo signal, and the value of this current depends on the specific form of these functions.

$$I_0 = \int\limits_{\nu} \frac{\bar{e}_0 \cdot \gamma(\nu)}{h\nu} \cdot \frac{\partial \Phi_0}{\partial \upsilon} \cdot d\upsilon$$

where $\bar{e}_0$ – charge of a single charge carrier of this type with its sign;
$\gamma(\nu)$ – quantum output at a given wavelength;
$h\nu$ – energy of one absorbed quantum;
Φ_0 – amplitude of the variable component of the absorbed stream;
υ – charge drift speed.

Extreme cases of generation of non-core charge carriers of practical interest are the following cases:

– uniform intensity of the electric field (characteristic for detecting *VD* and infrared radiation);

– uniform density of a bulk charge (characteristic for detecting *VD* and infrared radiation);

– local one, including superficial, generation of a photo signal (characteristic for the detection of *UV* and *VD*);

– uniform in volume of the current-generation signal (characteristic for detecting VD and infrared radiation).

The dependence of the output current of the photo signal in the external circle on the modulation frequency (ω), the structural parameters (x_0, μ), operating mode (V_0) and the generated current (I_0) is determined as:

$$I = \frac{I_0 \cdot V_0\mu}{\omega x_0^2} \cdot \sin\frac{\omega x_0^2}{2V_0\mu} \cdot \sin\omega\left(t - \frac{x_0^2}{2V_0\mu}\right), \qquad (5)$$

In the case of uniform tension of the electric field in the crystal and the surface generation of current, which is possible in a case when receiving relatively shortwave (*UV*) emission by a photodiode with a very high-resistance base, the complete depletion of the high-resistance region occurs at very small bias voltages (in comparison with the working ones), the limiting frequency is defined as:

$$f_{\text{гр}} = \frac{\omega_{гр}}{2\pi} \approx 1{,}391 \ldots \frac{2V_0\mu}{2\pi x_0^2},$$

Rising time τ, according (4) in this case is determined as:

$$\tau = 0{,}356\frac{x_0^2}{V_0\mu},$$

The case of surface photocurrent generation with uniform volume density of a charge within a crystal arises when receiving relatively short-wave radiation by a photodiode with a uniformly doped base at a bias voltage, which provides the width of the volume charge region, is exactly equal to the thickness of the crystal at a given degree of its doping. In this case, the limiting frequency is defined as:

$$f_{\text{гр}} = \frac{\omega_{\text{гр}}}{2\pi} = \frac{2}{2\pi t} = 2\frac{2V_0\mu}{2\pi x_0^2},$$

where t – time of charge carrier passing through SCR.

Accordingly, the rise time τ, according to (5), in this case will be defined as

$$\tau = 0{,}25\frac{x_0^2}{V_0\mu},$$

The situation of a uniform electric field and the uniform generation of charge carriers within a crystal arises when receiving long-wave radiation, which is relatively weakly absorbed by a photodiode with a very high-resistance base (pure *p-i-n* photodiode), resulting in a complete exhaustion of the high-resistance region occurs at very small bias voltages, in comparison with the working, ones . In this case, the current is carried by the carriers of the charge of both signs, which behave almost the same, but move in opposite directions and at different speeds. In this case, the boundary frequency (for example, a silicon-based photodiode) is defined as:

$$f_{\text{гр}} = \frac{\omega_{\text{гр}}}{2\pi} = \frac{Z}{2\pi t_n} \approx 0{,}7\cdot\frac{2V_0\cdot\mu_n}{2\pi x_0^2} = 2{,}1\cdot\frac{2V_0\mu_P}{2\pi x_0^2},$$

where $Z = \omega t_n$.

Accordingly, the rise time τ, according to (4), in this case will be defined as:

$$\tau \approx 1{,}429\frac{x_0^2}{V_0\mu_n} = 0{,}238\frac{x_0^2}{V_0\mu_p}, \tag{6}$$

The uniform generation of charge carriers and the uniform volume density of a charge within a crystal arises when receiving long-wave radiation by a weakly absorbed photodiode as compared with a uniformly doped base at a bias voltage that provides the width of the space charge region equal to the thickness of the crystal. As in the previous case, the uniform electric field and the uniform generation of charge carriers inside the crystal, the total current will be equal to the sum of the current of the carriers of both signs:

$$I = \frac{2}{3}I_0\sqrt{\frac{9+\omega^2(t_2+t_1)^2}{(1+\omega^2t_1^2)(4+\omega^2t_2^2)}}\cdot\sin(\omega t + \Delta\Box), \tag{7}$$

where t_1 and t_2 accordingly t_p and t_n.

Expression (7) describes the dependence of the output current of a photo signal in the external circle on the modulation frequency (ω), the design parameters $\left(t_i = x_0^2/2V_0\mu_i\right)$ and the value of the generated current (I_0), which is determined, in general, by the power and wavelength of the absorbed radiation. Proceeding from this, the boundary frequency in this case will be determined as:

for p-type

$$f_{\text{гр}}^{(p)} = \frac{\omega_{\text{гр}1}}{2\pi} = 0{,}859\frac{2V_0\mu_n}{2\pi x_0^2} = 2{,}577\frac{2V_0\mu_p}{2\pi x_0^2},$$

for n-type:

$$f_{\text{гр}}^{(n)} = \frac{\omega_{\text{гр}2}}{2\pi} = 0{,}406\frac{2V_0\mu_n}{2\pi x_0^2} = 1{,}218\frac{2V_0\mu_p}{2\pi x_0^2},$$

Accordingly, the rise time τ, according to (3.10), in this case will be defined as:

for p-type

$$\tau = 0{,}388\frac{x_0^2}{V_0\mu_p}, \tag{8}$$

for n-type:

$$\tau = 0{,}821\frac{x_0^2}{V_0\mu_p}, \tag{9}$$

Thus, depending on the method of generating non-core charge carriers, the magnitude of the growth time of the transient characteristic of the photodiode can differ almost fourfold.

In our case, the so-called *p-i-n* photodiode is considered on the basis of high- resistance silicon (resistivity not less than 20 kOm) of p-type conductivity. The operation of such a photodiode includes detecting radiation with a wavelength of about 1 μm. Since the optical radiation of such a wavelength is known [4], is absorbed in silicon at a depth of up to 1 mm, the construction of a photodiode requires a thickness of silicon crystals of 500 microns and the creation of a reflective contact on the back of the crystal that provides dual passage of radiation through a crystal of a photodiode (Figure 1). At the same time, a special bias volage is applied to the *p-n* transition to extend the space charge region to the entire thickness of the crystal (500 μm). In this case, the bias voltage is increased to the pre-rupture state to reduce the rise time of the transient characteristic. At the same time, the inverse current increases and sensitivity increases too.

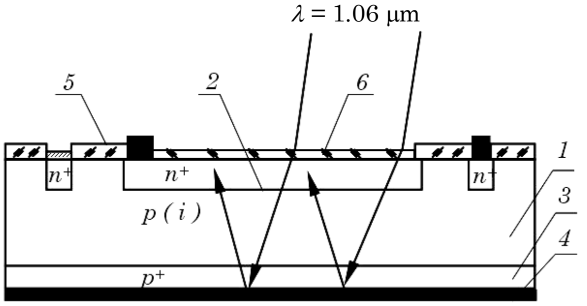

Fig. 1 – Schematic representation of the *p*-i-*n* crystal structure of the photodiode and the passage of the incident beam of optical emission (λ = 1.06 μm) in its volume: 1 – crystal *p-i-n* photodiode; 2 – *p-n* transition; 3 – layer *p* + conductivity type
4 – ring metallization (aurum) on the back of the crystal; 5 – silicon dioxide; 6 – illuminating the coating (silicon dioxide)

Based on the mode of operation of the photodiode, in order to solve the optimization problem, i.e., to reduce the rise time of the transient characteristic of the photodiode, it is necessary to select two of the four cases listed above, which are specific of detecting infra-red radiation, which includes a wavelength of about 1 μm:

- case of uniform electric field tension;
- case of uniform density of a space charge.

For these cases, the value of the rise time of the transient characteristic is determined according to formula (6), as well as expression (9). According to these expressions, the rise time of the transient characteristic of the photodiode may differ by 3.5 times; therefore, for the preliminary evaluation, the formula (9) was chosen as such, which is worse than the possible values.

Expression (8) shows that there are two ways to reduce the rise time of the transient characteristic. One that is used in the development of *p-i-n* photodiodes – an increase in the bias voltage on the *p-n* transition, which stands for the denominator of the formula (9). And the second one is a decrease in the width of an SCR which is in the numerator of formula (9) in a square. The elimination the double passage of optical radiation through an SCR photodiode, which is practically equal to its thickness (500 microns) multiplied by two (1000 microns), the gain in reducing the rise time of the transient characteristic can be fourfold!

On the basis of the above calculations, a new design of the *p*-i-*n* photodiode, which, under all other conditions, will provide less value of rise time of the transient characteristic, compared with the analogue of the FD-255A [5]. In this device the rise time value is equal to 40 ns. Our approach allows to reduce this value fourfold up to 10 ns.

Fig. 2 – Appearance of the proposed photodiode

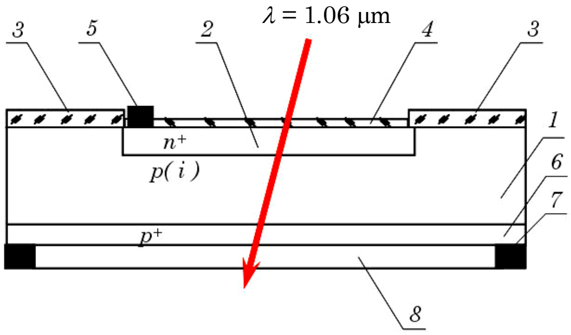

Fig. 3 – An example of a photodiode design with a reduced time of increase in the transient response: 1 – area *p*- conductivity type; 2 – area *n*- conductivity type; 3 – silicon oxide layer; 4 – antireflective layer of silicon oxide; 5 – an ohmic contact from the front side; 6 – area p^+ - conductivity type; 7 – an ohmic contact with the back side; 8 – hole in ohmic contact with the back side

Figure 2 shows the appearance of the proposed photodiode. Figure 3 is a schematic representation of his design.

The difference in the proposed design of the photodiode in the following.

The contact on the back of the crystal of the photodiode, as shown in Figure 3, is not continuous but with an aperture. Such a hole is the projection of a photosensitive element on the reverse side of the crystal of a photodiode. Such a change in design reduces the rise time of the transient characteristic, according to the calculation, which is the least four times up to 10^{-8} seconds. At the same time there is a loss of sensitivity for the working wavelength by about a quarter. This disadvantage is compensated by the use of a modern amplifier capable of amplifying the electric signal starting from 10^{-12} A. The thickness of the crystal of the photodiode should be no more than 500 microns.

The photodiode crystals presented in Figure 1 were made using the standard technology described in [6], which provides in the creation of *p-n* transition by the method of diffusion of phosphorus into a substrate of silicon of *p*-type conductivity.

Also, in order to improve the reverse (dark) current of the photodiode, an iso typically protective ring is formed around the photo of the sensitive element. To improve the ohmic contact on the reverse side of the crystal, the p^+-type conductivity layer is formed by the boron diffusion method. Ominous contacts are made of aurum by the method of thermal evaporation.

According to standard methods [7] on the crystals created, the value of current monochromatic sensitivity and rise time were investigated. Figure 4 shows a typical oscillogram of the rise time of the photodiode. It is well seen that the performance of the newly created photodiode is better than the serial FD-255A and is about 9 ns compared with 37 ns one of the analog.

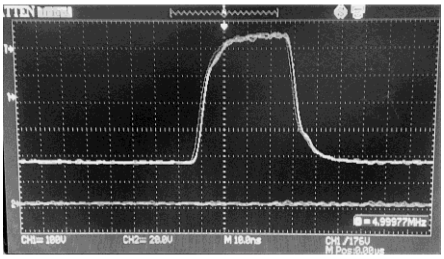

Fig. 4 – Typical oscillogram of the rise time of the proposed photodiode

The created photodiode is applied in a precision measurer of length (1 m).

4. CONCLUSION

Consequently, as a result of the research, the factors influencing the rise time of the photodiode. The photodiode on the basis of high-ohmic silicon of *p*-type conductivity with a minimized rise time was developed. The magnitude of the rise time of this photodiode is less than 9 ns compared to 37 ns in the analogue of the FD-255A one.

p-i-n фотодіод на основі кремнію з малим часом зростання

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Досліджено та проаналізовано фактори, що впливають на час виникнення фотодіоду. Використовуючи отримані результати, був розроблений фотодіод на основі високомічного кремнію провідності *p*-типу з мінімальним часом підйому. Пропонована конструкція. містить контакт на задній частині кристала фотодіода, який не є безперервним, але має отвір. Такою діркою є проекція світлочутливого елемента на зворотній стороні кристала фотодіоду. Значення часу підйому цього фотодіоду не перевищує 9 нс порівняно з 37 нс у аналозі FD-255A.

Ключові слова: Фотодіод, Час зростання, Гранична частота, Генерація струму.

p-i-n фотодиод на основе кремния с малым временем нарастания

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Исследованы и проанализированы факторы, которые влияют на время нарастания фотодиода. Используя полученные результаты, был разработан фотодиод, основанный на высокоомном кремнии с проводимостью *p*-типа с минимальным временем нарастания. Предлагаемая конструкция. содержит контакт на задней части кристалла фотодиода, который не является непрерывным, но имеет отверстие. Такая дырка представляет собой проекцию светочувствительного элемента на обратной стороне кристалла фотодиода. Величина времени нарастания этого фотодиода составляет не более 9 нс по сравнению с 37 нс в аналоге FD-255A.

Ключевые слова: Фотодиод, Время нарастания, Граничная частота, Генерация тока.

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