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HIGH-RESISTIVITY *p*-TYPE SILICON-BASED *p-i-n* PHOTODIODE WITH HIGH RESPONSIVITY AT THE WAVELENGTH OF 1060 nm

The paper presents the results of development, optimization and improvement of p–i–n photodiode technology based on high-resistance p-type silicon with increased responsivity at a wavelength of 1060 nm. The optimal material was selected and the technological modes optimal for solving the set task were established and worked out in the course of research.

Keywords: photodiode, silicon, sensitivity, technological mode.

According to ISO 2047 [1], the near-infrared (**IR**) region of the spectrum of optical radiation is characterized by the spectral range from 780 to 3000 nm. Various primary transducers are used to detect infrared radiation in this region of spectrum.

To study the energy parameters of infrared radiation, cavity and flat heat flux converters are used [2], which are nonselective and have high inertia. Devices and thermoelectric transducers, which convert thermal energy into electricity, are widely used as sensors of thermal radiation [3]. Modules based on anisotropic thermocouples are responsive parts of heat receivers. Thermoelectrically homogeneous anisotropic single crystals can be used to directly convert thermal energy into electrical energy [4]. But, like cavity transducers, they are non-selective and have high inertia.

Semiconductor-based photodetectors with a spectral range of sensitivity corresponding to the above-mentioned spectral range are effective for solving the problem of radiometry of the near-IR region of the spectrum [5]. One of the basic materials used in this field of electronics is silicon. The spectral sensitivity range of silicon photodiodes is from 380 to 1100 nm with a peak spectral response wavelength of 800—900 nm. This spectral range is interesting because it is covered with most infrared lasers and LEDs with operating wavelengths of 850, 900, 950, 1060 nm [6].

Obviously, increasing the responsivity of photodiodes is a high-priority task, the solution of which offers ample scope for optoelectronic equipment that uses such photodiodes. In particular, there is a task to develop and produce photodiodes with modulation-flux high current monochromatic and pulse responsivity.

This work is dedicated to improving and testing the process that would provide photodiodes based on high-resistivity *p*-type silicon. Such photodiodes would simultaneously have an increased current monochromatic responsivity across the modulated flux ($f = 20 \pm 5$ kHz) at the operating voltage $U_{op} = 30$ V and a pulse responsivity at the wavelength $\lambda = 1060$ nm (pulse duration $\tau = 500$ ns), at $U_{op} = 120$ V, namely, not less than 0.4 A/W.

We started by analyzing the parameters of high-responsivity silicon *p-i-n* photodiodes manufactured abroad. We established that products of Orion (PD 342, Russia) [7] and Sensors Inc. (BPX 65, USA) [8] to be the best in the field. It was found that despite the increasing need of the market for devices designed for $\lambda_{op} = 1060$ nm, Sensors Inc. produces low-voltage photodiodes operating at the wavelength of $\lambda_{op} = 850$ nm. And products of Orion Sc&PrCo have relatively high dark currents (up to 7 μA) and capacitance of photodiodes (up to 20 pF) at low-current responsivity values (0.2 A/W), that cannot satisfy the needs of customers of the market in full. Thus, the analysis has shown that none of the known photodiodes meets the requirements listed in the purpose of this work.

The research was conducted simultaneously on two different materials. The first one (Si_1) is a *p*-type silicon with lifetime of minority charge carriers $\tau_1 = 1400$ μs and resistivity $\rho_1 = 16$ kOhm. The second one (Si_2) had the following parameters: $\tau_2 = 1800$ μs and ρ_2 changing from 14 kOhm at one end of the ingot to 25 kOhm at the other end of the ingot. The wafers made from the second ingot were monitored for resistance and launched into production as two different materials in order to collect statistics on the dependence of the parameters of obtained devices on the initial resistance of the material.

Methods of Measurements

Current monochromatic responsivity $S_{I\lambda}$ was controlled by the method of comparing responsivity of the investigated photodiode (**PD**) with the responsivity of the reference one, which was certified by the metrological department of the enterprise. Measurements were performed under illumination of the PD with a modulated radiation flux of $f_{mod} = 20$ kHz and a power of below $1 \cdot 10^{-3}$ W. Load resistance of the responsive element (**RE**) was R_L = 10 kOhm and operating voltage U_{op} = 30 V. Pulse responsivity S_p was controlled at pulse durations τ_p = 500 ns and U_{op} = 120 V. Both the emitter and the optical system were made to illuminate only one PD responsive element. A voltmeter was used to measure first the voltage of the photosignal at the output of the reference photodetector (U_{st}), and then, without changing the power supply mode of the emitter, the voltage at the output of the tested PD (U_{i}).

The current monochromatic and pulse responsivity of the i^{th} RE were calculated by the formulas:

$$S_{i.I\lambda} = S_{I\lambda.\text{st}} U_i \,/\, U_{\text{st}}; \tag{1}$$

$$S_{i.\text{p}} = S_{\text{p.st}} U_{\text{i}} \,/\, U_{\text{st}}, \tag{2}$$

where U_i is the photosignal voltage of the i^{th} RE of the tested PD;
U_{st} is the photovoltaic voltage of the reference PD;
$S_{I\lambda.\text{st}}$, $S_{\text{p.st}}$ are current monochromatic and pulse responsivity of the reference PD.

Dark currents of the PD I_{d} were measured at the supply voltage of 120 V in accordance with GOST 17772-88, and their specific values were calculated by the formula [9]

$$I_{\text{d.spec}} = I_{\text{d}} \,/\, A_{\text{RE}}, \tag{3}$$

where A_{RE} is the area of the responsive element.

Experimental Details

The devices were manufactured using standard planar technology [10]. Parameters were regulated and technological modes were selected by optimizing and establishing the thermal operations that would ensure the required parameters.

Diffusion process is crucial in the technology of manufacturing semiconductor devices. To obtain the optimal concentration of non-basic charge carriers N_d, we performed two-stage diffusion from solid phosphorus sources.

After diffusion of phosphorus, the surface resistance ρ_{s} of the wafers, dark currents I_{d}, and resistivity S_{p} were monitored in order to inspect the wafers for quality and correct the technological process. The optimal values of ρ_{s} were experimentally established to be

$$2{,}7 \geq \rho_{\text{s}} \geq 2{,}5 \text{ Ohm/sm} \tag{4}$$

At $\rho_{\text{s}} \geq 2.7$ Ohm/sm, increase in I_{d} was observed above the set values.

When relation (4) was true for silicon type Si_1, values of S_{p1} at the level of 0.3—0.35 A/W (U_{op} = 120 V) were observed. For Si_2 silicon type, values S_{p2} were observed at the level of 0.34—0.37 A/W (U_{op} = 120 V). Si_2 material (14 kOhm) under these conditions had a reduced level of currents and S_{p2} at the level of 0.25—0.27 A/W (0.3 A/W at the PD output) after the diffusion of phosphorus. For this reason, it was deemed advisable to test it any further.

To ensure the qualitative parameters of the PD, the optimal bohr diffusion modes were experimentally established for the maximum possible restoration of charge carriers lifetime, which was reduced during the previous thermal procedures.

Results and Discussion

Thus, the results of the study allowed establishing that the photodiodes based on the selected materials and manufactured by the proposed technology achieved the following responsivity values:

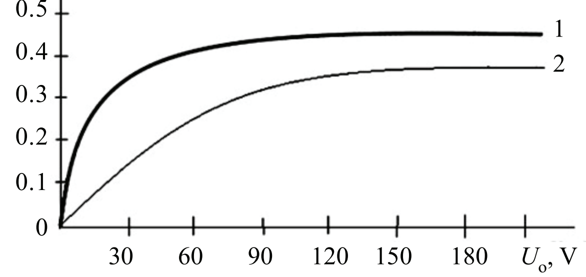
— for Si_1
S_{p1} = 0.36—0,39 A/W ;
$S_{I\lambda 1}$ = 0.4—0,43 A/W ;
$I_{\text{d.spec1}}$ = 7—11 nA / mm^2 (U_{op} = 120 V);

— for Si_2
S_{p2} = 0,38—0,42 A/W;
$S_{I\lambda 2}$ = 0.42—0,5 A/W;
$I_{\text{d.spec2}}$ = 10—15 nA / mm^2 (U_{op} = 120 V).

As to the RE of the photodiode crystal, the maximum obtained value of the current monochromatic responsivity $S_{I\lambda 2}$ = 0,52 A/W was reached for Si_2. The capacitance of the devices reached 11—15 pF for Si_2, while for silicon of the Si_1 type it was slightly higher, which is, of course, natural for a material with lower resistance.

The analysis of the results allowed establishing statistical relationship between S_{p} and $S_{I\lambda}$. The devices with S_{p} = 0.36—0.39 A/W simultaneously provided $S_{I\lambda}$ = 0.43—0.45 A/W, while the devices with S_{p} = 0.4—0.43 had $S_{I\lambda}$ = 0.46—0.5 A/W.

The obtained averaged curve of the dependence of the current pulse monochromatic sensitivity on the operating voltage at the *p–n* junction is shown in the **figure**. It illustrates that the sensitivity in a material with higher resistance is saturated at lower voltages than in one with lower resistance. The Si_2-based devices with $\rho \approx 25$ kOhm reach the maximum sensitivity values at a voltage of 45—60 V. At U_{op} = 60—120 V, the value of S_{p} remains unchanged. A slightly different pattern is



A graph showing the dependence of the current pulse monochromatic responsivity on the operating voltage at the *p–n* junction obtained for silicon PDs with $\rho \leq 25$ kOhm (*1*) and ρ = 16 kOhm (*2*) observed in Si_1 with ρ_1 = 16 kOhm. Here saturation is achieved at 80—100 V. This is explained by the fact that in a more resistive material, depletion of charge carriers in the *i*-region occurs faster, i.e., at lower voltages.

Heavy doping of the extreme n^+ and p^+ layers makes them conductive, and the maximum value of the electric current is reached in the *i*-layer. But since there are no free carriers in the *i*-layer, there is no electric current, so due to radiation of the *i*-layer, free electron-hole pairs are formed in it. These pairs quickly separate and move in opposite directions to their electrodes. As a rule, not all absorbed quanta of light create electron-hole pairs. In order to take this fact into account, one should use the measure of effectiveness of conversion of photons into electric current, or the so-called quantum efficiency (quantum yield) of the photodetector.

Quantum efficiency (output) of a photodiode is the ratio of the number of electrons born per second to the number of photons incident on the PD. Quantum efficiency (dimensionless quantity) is defined as [11]

$$\eta = \frac{N_{\mathrm{e}}}{N_{\mathrm{ph}}} = \frac{I_{\mathrm{ph}} / e}{P / (h\nu)} = \frac{I_{\mathrm{ph}} h\nu}{eP}, \qquad (5)$$

where N_{ph} is the number of photons falling on the detector per unit time;
N_{e} is the number of free electrons (or electron-hole pairs) born as a result;
I_{ph} is photocurrent;
e is electron charge;
h is Planck constant;
ν is radiation frequency;
P is optical radiation power.

To create an electron-hole pair, the energy $h\nu$ of the absorbed quantum must be sufficient for the transition of an electron from the valence band to the conduction band, i.e., the condition $h\nu \geq E_g$ must be met. The current monochromatic sensitivity is defined as [12]

$$S_{I\lambda} = \frac{\lambda}{1.234}\eta. \qquad (6)$$

Given the maximum obtained value (for finished devices) $S_{I\lambda}$ = 0,5 A/W, we derive that $\eta \approx 58\%$. According to [11], this value is close to the theoretical limit.

Note that the radiation interaction is only effective in the *i*-layer. When photons hit the p^+ and n^+ layers, they produce diffusion current, which has high inertia and impairs speed response.

That is why we manufactured the photodiodes with as wide a space charge region as possible, so that it could completely absorb all the incident light. After all, the obtained quantum efficiency, although approaching the theoretical one, is not the maximum value, and this result can still be improved.

REFERENCES

1. *Optics and photonics — Spectral bands*. ISO 20473: 2007. ISO Focus № 5, 2007, 72 p. (ISO standard). https://www.iso.org/standard/39482.html

2. Kmito A. A., Sklyarov Yu. A. *Pirgeliometriya* [Pyrgeliometry]. Leningrad, Gidrometizdat, 1981, 232 p. (Rus)

3. Pavlov A. V., Chernykov A. I. *Priyemniki izlucheniya avtomaticheskikh ustroystv* [Receivers of radiation of automatic devices]. Moscow, Energy, 1974, 274 p. (Rus)

4. Ashcheulov A. A., Snarsky A. A., Coats A. F. [Anisotropic thermocouples]. *Fizika i tekhnika poluprovodnikov*, 1997, vol. 31, no. 11, pp. 1281-1298. (Rus)

5. Verbytsky V. G., Vikulin I. M., Vorobienko P. P. et al. *Rozrobka vysokoefektyvnykh mikro-, nanotekhnolohiy optoelektroniky i komunikatsiynykh system na yikh osnovi* [Development of highly efficient micro-, nanotechnologies of optoelectronics and communication systems based on them]. Kyiv, LOGOS, 2009, 302 p. (Ukr)

6. Vigdorovich E. N. *Fizychni osnovy, konstruktsiya i tekhnolohiya optoelektronnykh prystroyiv* [Physical bases, design and technology of optoelectronic devices]. MGUP, 2011, 205 p. (Ukr)

7. *FD 342 Certificate*. Orion Scientific and Production Company. http://www.orion-ir.ru/ru/product.html

8. *BPX 65 photodiode certificate*. Sensors Inc. http://www.digikey.com/product-detail/en/BPX%2065/BPX%2065-ND/2205355

9. GOST1772-88. [*Radiation receivers. Semiconductor photovoltaic and photodetector devices. Methods of measuring photoelectric parameters and determination of characteristics*]. Moscow. Izdatel'stvo standartov, 1988,158 p. (Rus)

10. Filachev A. M., Taubkin I. I., Trishenkov M. A. [*Solid state photoelectronics. Photodiodes*]. Moskow, Fizmatkniga, 2011. (Rus)

11. Noikin Yu. M., Makhno P. V. *Fizicheskiye osnovy opticheskoy svyazi: elektronnoye uchebnoye posobiye* [Physical bases of optical communication: electronic textbook]. Rostov-on-Don, SFU, 2011, 355 p. (Rus)

12. P. K. Cheo. *Volokonnaya optika: Pribory i sistemy* [Fiber optics: Devices and systems]. Moscow, Energoatomizdat, 1988, 280 p. (Rus)

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p–i–n-ФОТОДІОД НА ОСНОВІ ВИСОКООМНОГО КРЕМНІЮ *p*-ТИПУ З ПІДВИЩЕНОЮ ЧУТЛИВІСТЮ НА ДОВЖИНІ ХВИЛІ 1060 нм

Ефективними для вирішення завдань радіометрії ближньої ІЧ-області спектру — від 780 до 3000 нм — є фотоприймачі на основі напівпровідників, спектральний діапазон чутливості яких відповідає зазначеному спектральному діапазону. Попри потребу, на ринку відсутні фотодіоди з високою струмовою монохроматичною чутливістю на модульованому потоці та імпульсною чутливістю на довжині хвилі 1060 нм (не менше 0,4 А/Вт), які б характеризувалися низькими питомими темновими струмами та ємністю.

Одним з основних використовуваних матеріалів в цій галузі електроніки є кремній. Спектральний діапазон чутливості кремнієвих фотодіодів складає від 380 до 1100 нм з максимумом спектральної характеристики в області 800 — 900 нм. В цьому діапазоні працює більшість ІЧ-лазерів та світлодіодів.

У цій статті представлено результати розробки, оптимізації та вдосконалення технології p–i–n-фотодіоду на основі високоомного кремнію p-типу з підвищеною чутливістю на довжині хвилі 1060 нм. В процесі досліджень було підібрано матеріал з оптимальним рівнем часу життя неосновних носіїв заряду та опором. Встановлено і відпрацьовано технологічні режими, оптимальні для вирішення поставленої задачі.

Запропоновано режими дифузії фосфора, які дозволяють отримати оптимальні концентрації неосновних носіїв заряду. Для забезпечення якісних параметрів фотодіодів експериментально встановлено режими дифузії бора для максимального відновлення часу життя носіїв заряду, який знижувався під час термічних операцій.

Сформульовано основні критерії ширини n^+*- та* p^+*-областей та області просторового заряду для повного поглинання випромінювання.*

Отримано фотодіоди з підвищеною струмовою монохроматичною імпульсною чутливістю та чутливістю на модульованому потоці за умов забезпечення низьких рівнів темнових струмів та ємності фоточутливих елементів.

Досягнуто квантової ефективності порядку 58%, що наближається до теоретичної межі.

Ключові слова: фотодіод, кремній, чутливість, технологічний режим.

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p–i–n-ФОТОДИОД НА ОСНОВЕ ВЫСОКООМНОГО КРЕМНИЯ *p*-ТИПА С ПОВЫШЕННОЙ ЧУВСТВИТЕЛЬНОСТЬЮ НА ДЛИНЕ ВОЛНЫ 1060 нм

Представлены результаты разработки, оптимизации и улучшения технологии p–i–n-фотодиода на основе высокоомного кремния p-типа с повышенной чувствительностью на длине волны 1060 нм. В процессе исследований был подобран материал с оптимальным уровнем времени жизни неосновных носителей заряда и сопротивлением. Установлены и отработаны оптимальные для решения поставленных задач технологические режимы,.

Предложены режимы диффузии фосфора, которые позволяют получить оптимальную концентрацию неосновных носителей заряда. Для обеспечения качественных параметров фотодиодов экспериментально установлены режимы диффузии бора для максимального восстановления времени жизни носителей заряда, который снижался в процессе проведения термических операций. Сформулированы основные критерии выбора ширины n^+*- і* p^+*-областей и области пространственного заряда, соответствующей полному поглощению излучения.*

Получены фотодиоды с повышенной токовой монохроматической импульсной чувствительностью и чувствительностью на модулированном потоке при обеспечении низких уровней темновых токов и емкости фоточувствительных элементов.Достигнута квантовая эффективность порядка 58%, что приближается к теоретическому пределу.

Ключевые слова: фотодиод, кремний, чувствительность, технологический режим.

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