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The Characteristics of the *pin*-Structure with a Discrete Metallic Surface *i*-Region

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Abstract
Introduction. The interest in improving *pin*-structures continues to attract research attention in the field of developing such electronic devices as non-volatile memory, static voltage protection systems, *pin*-diodes with adjustable characteristics, etc. However, the issue of controlling the characteristics of *pin*-structures by applying a discrete metallization layer on the surface of the *i*-region remains to be understudied.
Aim. To study the effect of a discrete metallization layer on the *i*-region surface on the static and dynamic characteristics of the respective *pin*-structure, the level of defect compensation and the efficiency control of the *pin*-photodetector.
Materials and methods. The *pin*-structure under study comprised a p^+-boron-doped region; an n^+-phosphorus-doped region; an *i*-phosphorus-doped region; a semi-insulating substrate; a metallized substrate; a polysilicon control gate; and a silicon oxide dielectric layer. A two-dimensional numerical analysis of the potential distribution, as well as the concentration of free charge carriers and currents, was performed in the Synopsys Sentaurus TCAD environment.
Results. A two-dimensional analysis of discretely metallized *pin*-structures was performed. The stresses applied to the gates of the *i*-region, which compensated for the influence of defects formed by electron irradiation, were determined. Four *pin*-photodetector structures were simulated, in which the control gates were realized in the form of a metal–insulator–semiconductor (MIS) structure. The possibility of increasing the sensitivity of *pin*-photodetectors by applying specifically selected potentials to the gates was demonstrated.
Conclusion. Effects of a discretely metallized *i*-region of the *pin*-structure was studied. A method for correcting the characteristics of the irradiated *pin*-diode to the initial characteristics was proposed, which permits the use of such diodes in areas with a high radiation level. The design of a high-sensitivity photodetector is proposed, the control gates of which are located on the surface of the *i*-region. The low-doped *i*-region is split into two regions (*p*- and *n*–type conductivity).

Keywords: *pin*-controlled diode, *pin*-programmable diode, MIS gates of the *i*-region, Synopsys Sentaurus TCAD

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Квантовая, твердотельная, плазменная и вакуумная электроника

Оригинальная статья

Характеристики *pin*-структуры с дискретно металлизированной поверхностью *i*-области

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Аннотация

Введение. В настоящее время интерес к совершенствованию *pin*-структур продолжает оставаться в центре внимания разработчиков электронных устройств. К устройствам, в которых используются такие структуры, можно отнести энергонезависимую память, устройство защиты от статического напряжения, *pin*-диоды с регулируемыми характеристиками и др. Однако вопросу управления характеристиками *pin*-структур посредством использования дискретной металлизации на поверхности *i*-области уделено недостаточное внимание.

Цель работы. Исследование влияния дискретной металлизации поверхности *i*-области на статические и динамические характеристики *pin*-структуры, компенсацию дефектов, управление эффективностью *pin*-фотодетектора.

Материалы и методы. Исследуемая *pin*-структура состоит из *p*+-области, легированной бором; *n*+-области, легированной фосфором; *i*-области, легированной фосфором; полуизолирующей подложки; металлизации подложки; управляющего затвора из поликремния; слоя диэлектрика из оксида кремния. Двумерный численный анализ распределения потенциала, концентрации свободных носителей заряда и токов выполнялся в среде Synopsys Sentaurus TCAD.

Результаты. Выполнен двумерный анализ дискретно металлизированных *pin*-структур. Определены напряжения, подаваемые на затворы *i*-области, компенсирующие влияние дефектов, образованных электронным облучением. Проведено моделирование четырех структур *pin*-фотодетектора, в которых управляющие затворы выполнены в виде структуры металл–диэлектрик–полупроводник. Показана возможность увеличения чувствительности *pin*-фотодетектора подачей соответствующих потенциалов на затворы.

Заключение. Исследовано влияние дискретной металлизации *i*-области *pin*-структуры. Предложен метод коррекции характеристик облученного *pin*-диода до исходных характеристик. Тем самым появляется возможность использования таких диодов в электронике с высокими требованиями к работе в зонах с повышенной радиацией. Предложена конструкция фотодетектора повышенной чувствительности с управляющими затворами на поверхности *i*-области и с разделением структуры низколегированной *i*-области на две области *p*- и *n*-типов проводимости.

Ключевые слова: *pin*-диод управляемый, *pin*-диод программируемый, МДП-затворы *i*-области, Synopsys Sentaurus TCAD

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Introduction. *Pin*-diodes with control gates located on the surface of the *i*-region are increasingly attracting research attention due to their expanded functionality and the ease of integrating with other devices. A number of studies have reported the development of *pin*-diodes with a discrete metallization layer on the surface of the *i*-region. Thus, changing the switching time of controlled *pin*-structures was considered in [1]. Additionally, gate-controlled *pin*-diodes are applicable for the antistatic protection of integrated circuits [2]. Thus, a non-volatile memory device was developed on the basis of a *pin*-structure in [3]. The integration of controlled *pin*-structures into non-volatile memory was considered in [4, 5]. Recently, the use of 3D shutters in *pin*-structures has become widespread [6].

Some articles investigated the effect of radiation on instruments and devices. For example, in [7], the degradation of silicon n^+–n–p^+-structures as a result of exposure to high-energy $\left(10^{15}\ldots10^{16}\ \text{cm}^{-2}\right)$ electron/proton irradiation was studied. The study [8] aimed to investigate the effect of electron irradiation on the current-voltage curve (CVC) and low-frequency noise (current and $1/f$) of 4H–SiC *pin*-diodes.

In [9], the CVC and Schottky barrier of a *p*-type diode were studied depending on the dose of electron irradiation. During irradiation, the crystal structure and electrical properties of semiconductors may vary. In some situations, these parameters are varied intentionally to accurately adjust the speed and capacity of devices. In [10–12], the effect of high-energy particle irradiation on the dynamic characteristics of diodes was investigated. It is known that radiation may cause undesirable changes in diode characteristics [13]. A number of studies [14–16] were devoted to the effect of metal electrodes located on the surface of the *i*-region on the properties of respective *pin*-diodes.

This article is devoted to simulating silicon *pin*-diodes with a discretely metallized surface. The influence of defects, which are associated with electron irradiation of *pin*-diodes, on the CVC and opening time of such diodes was studied. The static and dynamic characteristics of *pin*-diodes were corrected by applying specifically selected potentials to the *pin*-structure gates. The voltages applied to the gates to compensate for the impact of defects were determined.

In addition, the article investigates the influence of metal electrodes located on the surface of the *i*-region to sensitivity of photodetectors based on *pin*-structures. Four different designs of *pin*-photodetectors were studied, the floating gates in which were realized in the form of a metal-insulator-semiconductor (MIS) structure. The effect of the gate geometry and applied potentials on the sensitivity of the photodetector was elucidated. In addition, the effect of splitting the low-doped *i*-region into two low-doped regions of *p*- and *n*-type conductivity on the sensitivity of the *pin*-photodetector was investigated. Simulations were performed in the Synopsys Sentaurus TCAD environment.

Simulation of *pin*-diodes. The Synopsys Sentaurus TCAD software can be used to describe the traps resulting from irradiation, which create additional energy levels in the band gap, as well as to consider the capture and storage of space charge in the traps. In order to study the effect of electron irradiation on the CVC and opening time of *pin*-structures, a completely irradiated structure was used. These structures are characterized by a uniform distribution of traps, which have parameters corresponding to those of electron irradiation [17]. For preliminary analysis and modeling, the structure presented in Fig. 1 was selected. During simulations, the geometric dimensions of the control electrodes and their potentials were selected such that the most effective impact on the CVC and switching time could be achieved.

Fig. 2 shows the CVC for the initial and electronically irradiated *pin*-structures across the range from 0 to 1.7 V. In the developed structure with a discretely metallized surface, the contribution of traps to the CVC is compensated by applying voltage to the gates. Positive voltages act similarly to traps, leading to a decrease in the angle of the CVC inclination. Under negative voltages, the opposite situation is observed, thus allowing the impact of defects on the CVC to be compensated. Voltages of different signs applied to the gates produce the best result in terms of correcting the CVC of *pin*-structures. Thus, when applying a negative voltage to the gate G1 $U_{\text{G1}} = -5.2\ \text{V}$ and a positive voltage to the gate G3 $U_{\text{G3}} = 5.2\ \text{V}$, a maximum increase in the slope of the CVC was achieved. An almost linear dependence was reveled between the gate compensating stresses and defect concentrations.

Defects in the *pin*-structure change the rate of the current rise. As a result, a correction of the switching characteristics is required in order to return the opening time to that of a defect-free *pin*-diode. As shown in [18], the switching characteristics are controlled

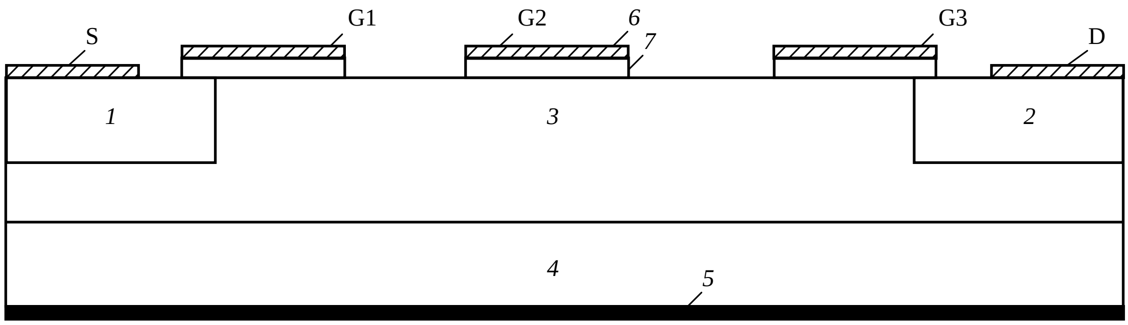

Fig. 1. Structure of the *pin*-diode under study: S – source; G1–G3 – gates; D – drain; *1* – p^+-region doped with boron with a concentration of $1 \cdot 10^{20}$ cm^{-3}; *2* – n^+-region doped with phosphorus with a concentration of $1 \cdot 10^{20}$ cm^{-3}; *3* – *n*-region doped with phosphorus with a concentration of $1 \cdot 10^{15}$ cm^{-3}; *4* – semi-insulating substrate; *5* – metallization of the substrate; *6* – polysilicon control gate with a thickness of 4 nm; *7* – layer of silicon dioxide dielectric with a thickness of 1.8 nm

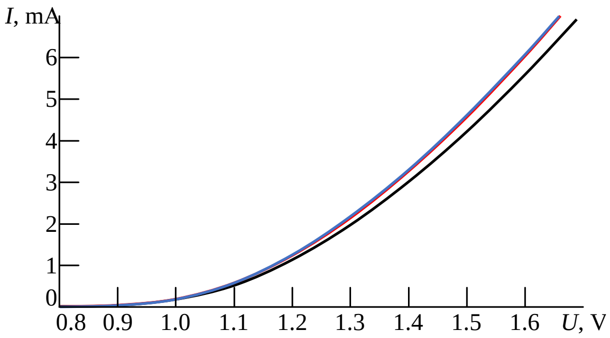

Fig. 2. Compensation of the *pin*-diode current-voltage characteristics (CVC) with additional gates. Red line – the initial diode CVC; black line – diode CVC after irradiation; blue line – diode CVC after irradiation and gate compensation ($U_{G1} = -5.2$ V; $U_{G2} = 0$; $U_{G3} = 5.2$ V)

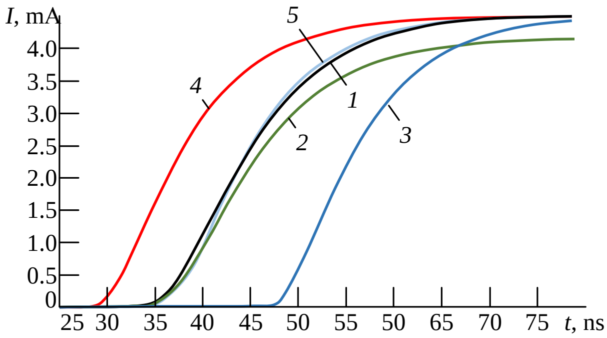

Fig. 3. Switching *pin*-diode characteristics: *1* – original (without defects); *2* – irradiated diode; *3* – irradiated diode with increasing opening time due to voltage at the compensating gate $(U_{G2} = -0.8\ \text{V})$; *4* – irradiated diode with decreasing opening time due to voltage at the compensating gate $(U_{G2} = 0.6\ \text{V})$; *5* – irradiated diode with compensating voltage at the compensation gates ($U_{G1} = -5.2$ V; $U_{G2} = -0.6$ V; $U_{G3} = 5.2$ V)

by the gates on the surface of *pin*-structures. Fig. 1 shows G1–G3 gates, which provide correction of the switching characteristics given in Fig. 3. The side gates (G1 and G3) provide adjustment of the current and opening time, thus allowing control of the CVC slope and switching characteristics. The introduction of the middle G2 gate into the model allows the opening time to be customized. When a positive bias was applied to G2, the opening time decreased (Fig. 3, *4*, $U_{G2} = 0.6\ \text{V})$, while a negative bias led to an increase in the opening time (Fig. 3, *3*, $U_{G2} = -0.8\ \text{V})$. The simultaneous use of three gates makes it possible to adjust the switching characteristics of the *pin*-diode quite accurately, as can be seen when comparing dependencies *1*, *2*, and *3* in Fig. 3. The correction results are displayed by dependence *5*.

Thus, the conducted simulations confirmed the possibility of correcting the characteristics of *pin*-structures exposed to electron radiation by applying three MIS gates to the diode surface and specifically selected potentials. Adjustable characteristics include the CVC and those of the opening of a *pin*-structure. The proposed method is suitable for correcting the deviation of the operating characteristics of an irradiated diode to its factory characteristics, thus allowing such diodes to be used in electronics meeting strict requirements for work in high-radiation areas. In addition, the proposed method ensures a longer service life of electronic devices.

Another research aim was to study the effect of metal electrodes (gates) located on the surface of the *i*-region on the sensitivity of *pin*-photodetectors. Four designs of *pin*-photodetectors were studied, in which the control gates were realized in the form of a MIS structure.

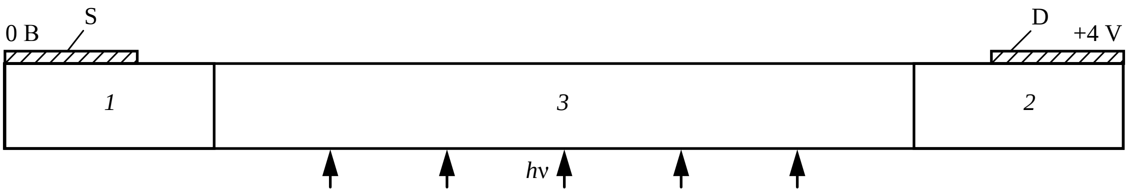

Fig. 4. Topology of the original *pin*-photodetector: S – source; D – drain; *1* – p^+ -area doped with boron with a concentration of $1 \cdot 10^{20}$ cm^{-3}; *2* – n^+-area doped with phosphorus with a concentration of $1 \cdot 10^{20}$ cm^{-3}; *3* – *i*–*n*-area doped with phosphorus with a concentration of $1 \cdot 10^{15}$ cm^{-3}; *h*ν – optical irradiation

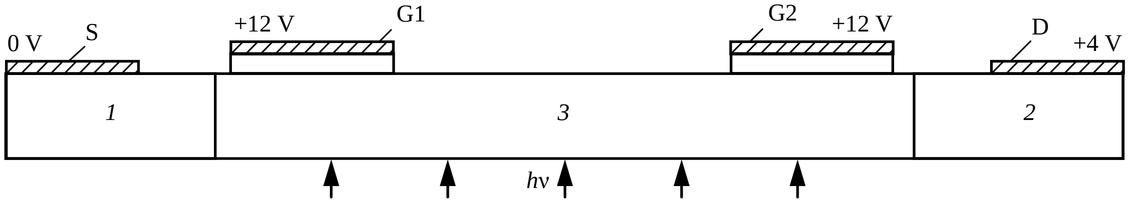

Fig. 5. Structure of the *pin*-photodetector with one-side paired control gates: S – source; G1, G2 – control gates; D – drain; *1* – p^+ -region with boron with a concentration of $1 \cdot 10^{20}$ cm^{-3}; *2* – n^+-region doped with phosphorus with a concentration of $1 \cdot 10^{20}$ cm^{-3}; *3* – *i*–*n*-region doped with phosphorus with a concentration of $1 \cdot 10^{15}$ cm^{-3}; *h*ν – optical irradiation. Gate thickness is 4 nm, gates dielectric thickness is 1.8 nm

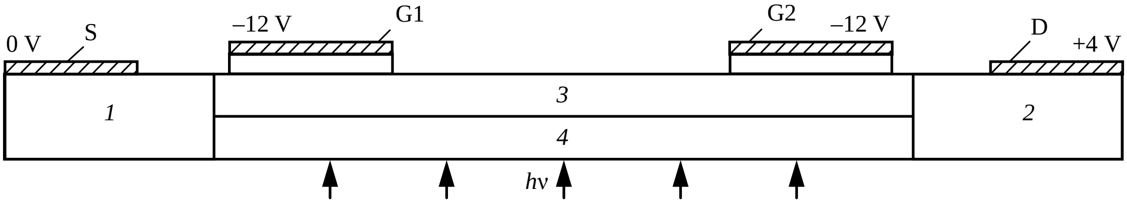

Fig. 6. Structure of the *pin*-photodetector with two-layer *i*-region and one-side paired control gates: S – source; G1, G2 – control gates; D – drain; *1* – p^+ -region doped with boron with a concentration of $1 \cdot 10^{20}$ cm^{-3}; *2* – n^+-region doped with phosphorus with a concentration of $1 \cdot 10^{20}$ cm^{-3}; *3* – *i*–*p*-region doped with boron with a concentration of $1 \cdot 10^{15}$ cm^{-3}; *4* – *i*–*n*-region doped with phosphorus with a concentration of $1 \cdot 10^{15}$ cm^{-3}; *h*ν – optical irradiation. Gate thickness is 4 nm, gates dielectric thickness is 1.8 nm

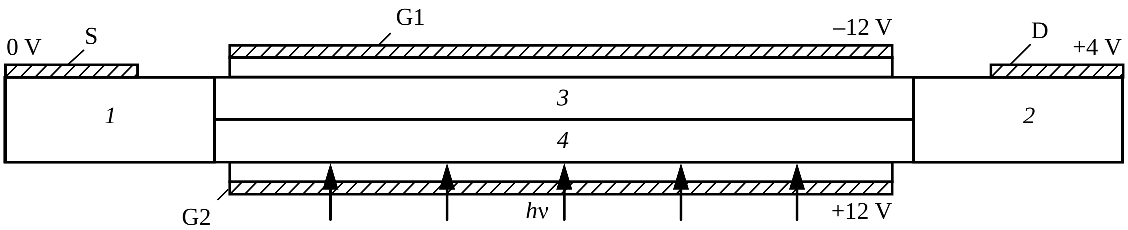

Fig. 7. Structure of the *pin*-photodetector with two-layer *i*-region and the and full-covering top and bottom control gates: S – source; G1, G2 – control gates; D – drain; *1* – p^+ - region doped with boron with a concentration of $1 \cdot 10^{20}$ cm^{-3}; *2* – n^+- region doped with phosphorus with a concentration of $1 \cdot 10^{20}$ cm^{-3}; *3* – *i*–*p*- region doped with boron with a concentration of $1 \cdot 10^{15}$ cm^{-3}; *4* – *i*–*n*- region doped with phosphorus with a concentration of $1 \cdot 10^{15}$ cm^{-3}; *h*ν – optical irradiation. Gate dielectric thickness is 1.8 nm, gates thickness is 4 nm

The scheme of the initial *pin*-photodetector is shown in Fig. 4. The effect of the gates located on the surface of the *i*-region was studied using a photodetector, the structure of which is shown in Fig. 5. The simulation results show that both the gate length in the direction of carrier drift and the potentials at the gates affect the sensitivity of the *pin*-photodetector rather significantly.

The next stage of the research was to elucidate the effect of splitting the low-doped *i*-region into two regions – *i*–*p* and *i*–*n* types – on the sensitivity of the *pin*-photodetector. Such a design is assumed to contribute to a more efficient separation of electron and hole flows, thereby reducing the recombination process. The studied structures are presented in Fig. 6 and 7.

Simulation of a *pin*-photodetector. In the process of modeling, the spectral characteristics of *pin*-photodetectors and the distribution of charge carriers in the *i*-region were studied, taking into account the Shockley–Read–Hall recombination for the four structures shown in Figs. 4–7. The parameters of the studied structures are detailed in the figure captions. In the structure shown in Fig. 5, the *i*-region is formed by doping with phosphorus (*i*–*n*). For the separation of charges, a potential of +12 V is applied to both gates. For the separation of charges in the structure in Fig. 6, where the *i*-region is doped with boron (*i*–*p*), a potential of –12 V is applied to both gates. For the separation of charges in the structure in Fig. 7, a potential of –12 V is applied to the gate G1 located on the *i*–*p*-region, while the potential +12 V is applied to the gate G2 located on the *i*–*n*-region. Voltages at the gates and drain are selected such that the greatest difference between the characteristics of the modified devices and those of the original photodetector could be achieved (see Fig. 4).

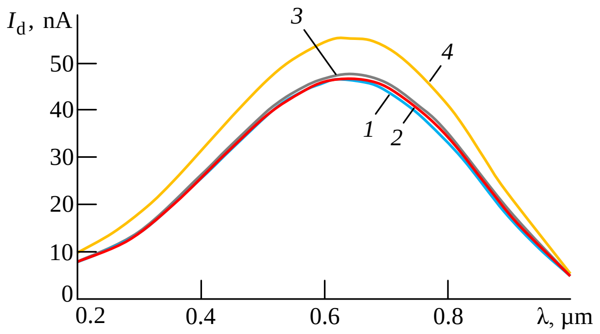

Fig. 8. Spectral characteristics for *pin*-photodetector structures: *1* – initial (see fig. 4); *2* – with one-side paired gates and one-layer *i*-region (see fig. 5); *3* – with one-side paired gates and two-layer *i*-region (see fig. 6); *4* – with full-covering gates and two-layer *i*-region (see fig. 7)

In studying the spectral characteristics of *pin*-photodetectors, a potential of +4 V was applied to the drain. The spectral composition and intensity of optical radiation were assumed to be the same for all topologies. The simulation results shown in Fig. 8 demonstrate that the spectral characteristics of both photodetectors are close, however, the photocurrent (sensitivity to optical radiation) is maximum in the *pin*-photodetector with full-covering gates and two-layer *i*-region (Fig. 7). A comparison of the characteristics shows that using of gates leads to a greater separation of electrons and holes in the *i*-region (Fig. 8, curves *1* and *2*). The splitting of the *i*-region into two layers with different conductivity types, along with extended gates on both sides of the structure (Fig. 7), permits a higher photocurrent to be achieved in comparison with the structure shown in Fig. 6.

The simulations performed in the Synopsys Sentaurus TCAD environment made it possible to study the effect of the Shockley–Read–Hall recombination on the distribution of charge carriers in the *i*-region of *pin*-photodetectors. Fig. 9 shows the results obtained for the four investigated structures. When the *i*-region is divided into two low-doped parts, electrons and holes pass through the semiconductors of the *i*–*n* and *i*–*p*-conductivity, respectively. In addition, their separation by the vertical field of full-covering gates (structure according to Fig. 7) occurs

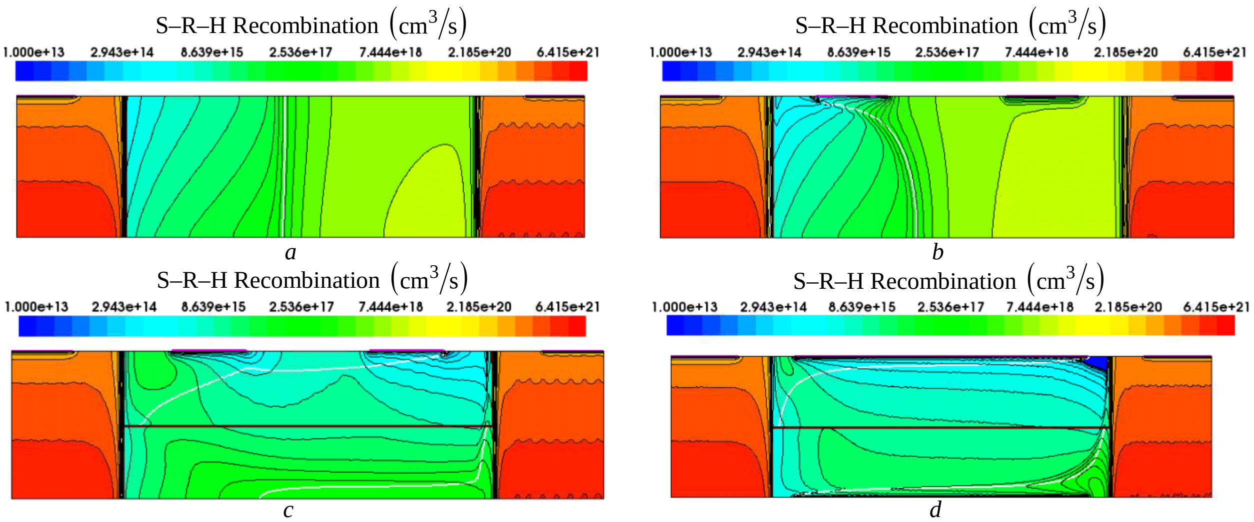

Fig. 9. Shockley–Read–Hall Recombination for the studied *pin*-photodetector structure: *a* – initial (see fig. 4); *b* – with one-side paired gates and one-layer *i*-region (see fig. 5); *c* – with one-side paired gates and two-layer *i*-region (see fig. 6); d – with full-covering gates and two-layer *i*-region (see Fig. 7)

more efficiently than when the gates are located on one side (structure according to Fig. 6) (Fig. 9, *c* and *d*). As a result, for topologies with a split *i*-region, the Shockley–Read–Hall recombination manifests itself to a lesser degree: the more efficiently the carriers are separated by the gate field, the less pronounced the Shockley–Read–Hall recombination becomes. Thus, the introduction of layers of different conductivity types in the *i*-region of *pin*-photodetectors in combination with full-covering gates on both sides, allows the photocurrent to be increased up to about 20%, compared to basic *pin*-photodetectors.

Discussion. The article solves the problem of controlling the characteristics of *pin*-structures using gates on the surface of the *i*-layer. Such problems are encountered in the development of non-volatile memory, static voltage protection devices, *pin*-diodes with adjustable characteristics, etc. The proposed method for correcting the characteristics of an irradiated *pin*-diode to its original characteristics opens up the possibility of using such diodes in electronics meeting strict requirements for work in high-radiation areas.

A 2D calculation of the distribution of the concentration of free charge carriers and potential in the *pin*-structure of a photodetector was carried out. A structure for a high-sensitivity photodetector featuring control gates on the surface of the *i*-region and the separation of the low-doped *i*-region structure into two regions with *p*- and *n*-types of conductivity was proposed. The conducted research confirmed that a discrete metallization of the surface of the *i*-region has a positive effect on the main characteristics of devices based on *pin*-structures.

Author's contribution

Alexander A. Danilenko, calculations in the program Synopsys Sentaurus TCAD; simulation of the of free charge carriers concentration distribution.

Alexey D. Ivanov, calculations of the current in the program Synopsys Sentaurus TCAD.

Vladimir L. Ivanov, a review of publications in the area of article subject.

Vladislav V. Marochkin, selection and analysis of calculation models of the package Synopsys TCAD.

Nikolay I.Mikhailov, discussion and analysis of the *pin*-structures physical models.

Vadim V. Perepelovsky, introduction and formulation of the problem; the results discussion.

Авторский вклад

Даниленко Александр Александрович – проведение расчетов в программе Synopsys Sentaurus TCAD; моделирование распределения концентрации свободных носителей заряда.

Иванов Алексей Дмитриевич – проведение расчетов токов в программе Synopsys Sentaurus TCAD.

Иванов Владимир Леонидович – обзор существующих публикаций в предметной области.

Марочкин Владислав Викторович – выбор и анализ численных моделей пакета Synopsys TCAD.

Михайлов Николай Иванович – обсуждение и анализ физических моделей *pin*-структур.

Перепеловский Вадим Всеволодович – введение в проблему; постановка задачи; обсуждение результатов.

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