Series of Photovoltaic Converters Based on Semiconductors with Intrinsic Photoconductivity

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Abstract

One of the ways to solve multiple problems of optical diagnostics is to use photovoltaic converters based on semiconductors with intrinsic photoconductivity slightly doped with deep impurities which form several energy levels with different charge states within the semiconductor′s bandgap. Peculiarities of physical processes of recharging these levels make it possible to construct photodetectors with different functionality based on a range of simple device structures.

The aim of this work is to analyze peculiarities of conversion characteristics of single-element photovoltaic converters based on semiconductors with intrinsic photoconductivity, to systematize their properties and to represent structures of photovoltaic convertors as a device structures suitable for implementation in measurement transducers of optical diagnostics systems.

Based on the analysis of the characteristics of the conversion characteristics of single-element photovoltaic converters based on semiconductors with intrinsic photoconductivity and the requirements for their design, a dash series of photovoltaic converters was developed for use in the measuring transducers of optical diagnostics systems. The possibility of constructing func-tional measuring transducers for multiparameter measurements of optical signals is shown.

Keywords: photovoltaic converter, device structure, deep impurity, conversion characteristic, measurement transducer.

Приборный ряд фотоэлектрических преобразователей на основе полупроводников с собственной фотопроводимостью

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Одним из способов решения многообразных задач оптической диагностики является использование фотоэлектрических преобразователей на основе полупроводников с собственной фотопроводимостью, слабо легированных глубокими примесями, формирующими несколько уровней с разными зарядовыми состояниями в запрещённой зоне. Особенности физических процессов перезарядки этих уровней позволяют создавать фотоприёмники с различными функциональными возможностями на основе ряда простых приборных структур.

Целью работы является анализ особенностей преобразовательных характеристик одноэлементных фотоэлектрических преобразователей на базе полупроводников с собственной фотопроводимостью, систематизация их свойств, и представление структур, представленных ФЭП в виде приборного ряда фотоэлектрических преобразователей для применения в измерительных преобразователях систем оптической диагностики.

На основе анализа особенностей преобразовательных характеристик одноэлементных фотоэлектрических преобразователей на базе полупроводников с собственной фотопроводимостью и требований к их конструкции разработан приборный ряд фотоэлектрических преобразователей для применения в измерительных преобразователях систем оптической диагностики. Показана возможность построения функциональных измерительных преобразователей для многопараметрических измерений оптических сигналов.

Ключевые слова: фотоэлектрический преобразователь, приборная структура, глубокая примесь, преобразовательная характеристика, измерительный преобразователь.

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Introduction

Optical diagnostics tasks are associated with registration and analysis of optical radiation parameters which are formed during interaction of probing light with an object studied and light-scattering media. In some cases, the source of radiation is the object itself. At the same time functional capabilities of optical diagnostics systems and performance of their measurement transducers are largely determined by photovoltaic converters that convert one or several parameters of optical irradiation including absolute and relative intensity of spectral lines, half-width, shape of spectral lines, etc. [1–4]. Therefore implementation of photovoltaic convertors (PVCs) based on semiconductors with intrinsic photoconductivity into measurement transducers for optical diagnostics is of great interest since that PVCs provide a set of new qualitative and quantitative characteristics using rather simple device structure [5].

The aim of this work is to analyze peculiarities of conversion characteristics of single-element photovoltaic converters based on semiconductors with intrinsic photoconductivity, to systematize their properties and to represent structures of presented PVC as a device structures range suitable for implementation in measurement transducers of optical diagnostics systems.

Fundamentals of photovoltaic converters based on semiconductors with intrinsic photo-conductivity

Physical principles of operations of PVCs based on semiconductors with intrinsic photoconductivity [5] could be described as integration of processes inside sensitive region volume associated with sequential recharging of various charge states of deep impurity (Figure 1). In photodetectors with intrinsic photoconductivity slightly doped with a number of acceptor impurities [5] the impurity forms two or three deep levels in several charge states. In this case performance of device structure with deep multiply charged impurities is determined, at large, by recombination processes through impurity levels [5, 6].

Several energy levels participating in formation of PVC conversion characteristics (Figure 1) provide switching capability for energetic, spectral and transition sensitivity characteristics of PVC making it possible to switch between several conversion subranges (regions). The physical nature of switching between different regions of conversion characteristics of PVC based on semiconductors with intrinsic photoconductivity slightly doped with deep multiple charged impurity is due to a change in lifetime and mobility [5] of minority carriers resulting from their redistribution over recombination levels and adherence of multiple charged impurity. For PVCs based on semiconductors with acceptor impurity the shift in lifetime and recombination constant with level population change reaches several decimal orders of magnitude [5–7] while multiple charged donor impurity (Se, S, Zn for Silicon) produces shifts below 1 %, which is due to the fact that the energy levels of the impurity are already filled (Figure 1, Se impurity).
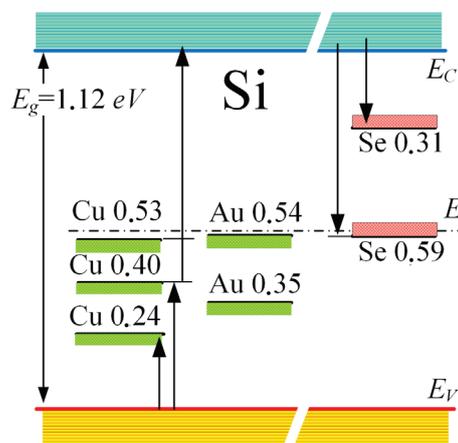
Figure 1 – Band diagram of Silicon doped with acceptor (Cu, Au) and donor (Se) impurities which form multiple charge levels, with the given values of the ionization energy

Formation of characteristics of PVCs with intrinsic photoconductivity based on semiconductors with a low concentration of deep multiply charged impurity is described by updated model of recombination processes for impurity with arbitrary number (i) of levels inside semiconductor′s bandgap [5, 6]. The modeling[1] determines dependencies (1) of impurity levels population for different charge states and dependencies of majority and minority carriers′ lifetime on the power density of optical radiation:

1. Shadurskaya L.I., Yarzhembitskaya N.V. [Method for calculating the lifetime of nonequilibrium charge carriers in semiconductors with several types of defects]. *Teoreticheskaya i prikladnaya mehanika* [Theoretical and Applied Mechanics]: sc. art. collection. – Minsk, 2005, vol. 18, pp. 217–223 (in Russian).

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$$\tau_n = \frac{\Delta n}{U_{n1} + U_{n2}}; \quad \tau_p = \frac{\Delta p}{U_{p1} + U_{p2}}. \tag{1}$$

PVC design is relatively simple an could be formed by photoresistive or surface-barrier device structure with different configuration of planar and/or two-sided system of electrodes some of which could be semitransparent or represent, for example, quarter-wave philter [4–5, 8]. The use of barrier regions (heterojunctions, Schottky barriers) in device structures makes it possible to obtain conversion characteristics with the inversion of sign. In this case the control action causing switching between different regions of conversion characteristics can be various factors [4–5, 9], including their combinations: input optical radiation intensity (internal control), lowering energy barrier height under photo-generated carriers injection through it (internal amplification of a barrier structure under forward bias), carriers injection from external bias source via additional electrode (external electrical control), recharging of multiply charged impurity levels by additional controlling optical radiation (external optical control). Functionality and conversion characteristics parameters of these PVCs could be controlled by appropriate choice of structure and basic semiconductor material, production technology, power supply and bias modes, additional optical radiation [5, 9].

PVCs with internal control

The most simple device structure that is formed by a bulk semiconductor with intrinsic photoconductivity slightly doped with deep impurity forming several levels inside bandgap for different charge states (Figure 1) and an applied ohmic contacts in planar (Figure 2a) or two-sided (Figure 2b) structure corresponds to PVC with internal control.

Figure 3 shows energy conversion characteristics of PVC with intrinsic photoconductivity doped with multiple charged acceptor (lines a and b for different semiconductor and impurity materials – indices i, j) and donor (line c) impurities. For comparison the energy sensitivity characteristic of fotodetector based on semiconductor with impurity conductivity (d) is also shown. For a PVC based on a semiconductor with intrinsic photoconductivity doped with a singly charged impurity only region I of energetic sensitivity characteristic is implemented. Internal control of the conversion characteristics type (Figure 3) is realized due to the fact that at low

intensities of the optical signal [5] photoconductivity is caused by energy transition between the valence band and the lower energy level of the multiply charged impurity in the charge state (-1, -2) that forms sensitivity region I (Figure 3). With a further increase in the intensity of optical radiation the lower level becomes completely filled and photoconductivity is formed also by higher level in the charge state (-2, -3). This leads to lengthening of PVC energy characteristic (region II on Figure 3), on a logarithmic scale, about twice comparing with energy characteristic of photodetectors with impurity conductivity. Region III is transitional and is characterized by a nonlinear dependence of the photocurrent i on the optical radiation intensity j. In characteristic′s regions I and II this dependence is linear. Significant increase of the dynamic range for PVCs with intrinsic photoconductivity is a positive property that determines the insensitivity of such PVCs to intense "flares" but it should be noted that absolute values of sensitivity of PVCs with intrinsic photoconductivity are lower than sensitivity of PVCs with impurity conductivity.
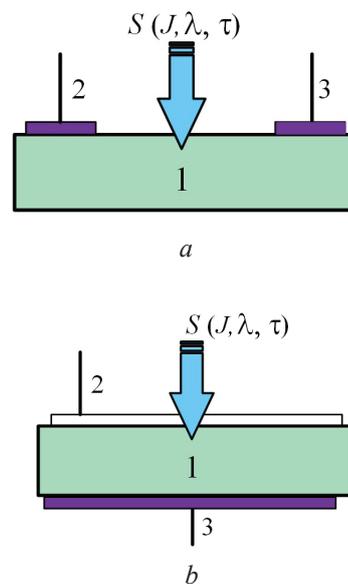
Figure 2 – Planar (a) and two-sided (b) device structures of a PVC with internal control: 1 – semiconductor with intrinsic photoconductivity slightly doped with deep impurity; 2, 3 – contacts; S – input optical signal

Switching between the sensitivity subrange, internally controlled by the intensity of the measured optical radiation itself leads not only to an increase in the dynamic range of the energy characteristic. The formation of subranges with different sensitivity due

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to transitions between levels with different ionization energies leads also to the shift in the "red" border of PVC′s spectral sensitivity. Combination of basic semiconductor material type (Silicon, Germanium, binary compositions) and impurity type (Fe, Pt, Au, Cu etc.) provides switching between spectral sensitivity characteristic types under the influence of the intensity of the input optical radiation with a different values of shift of sensitivity "red" border (Figure 4). Switching time between sensitivity subranges of PVC′s energy and spectral conversion characteristics is determined by the lifetime constant of charge carriers.
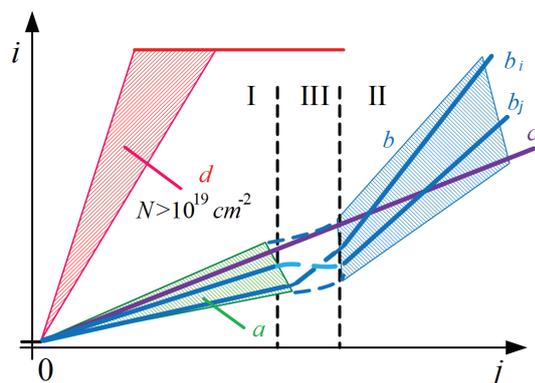

Figure 3 − PVC′s energetic conversion characteristics
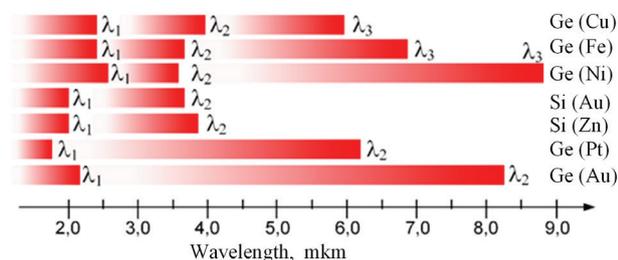

Figure 4 – Change of red border of spectral sensitivity for PVCs with multiply charged impurity centers for different materials

The use of optical filters in the form of films with a passband around wavelengths λ_1 and λ_2 makes it possible to form a single-element PVC with switchable narrowband spectral characteristics. Switching time between different characteristics is determined by the lifetime constant of charge carriers.

Note that switching between sensitivity subranges for all types of characteristics is realized only when using acceptor type impurities. Since the levels of the donor impurity are already filled at any injection level, the switching between subranges does not occur although the energy conversion characteristic of the PVC is lengthened (line *c* on Figure 3).

Photoresistive PVCs with external electrical control

Population of different levels of multiply charged impurity could be changed not only under the influence of changes in the intensity of the input optical radiation but also due to injection of charge carriers into photosensitive region via additional controlling electrode 4 (Schottky barrier) as shown on Figure 5.
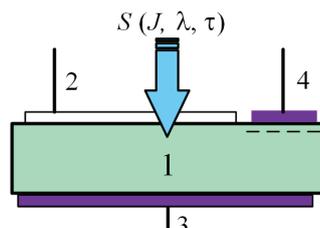

Figure 5 – Device structure of the PVC with external electrical control

The shape of conversion characteristics of PVCs with external electrical control does not differ from the characteristics of PVCs with internal control but switching between sensitivity subranges (Figures 3 and 4) can be performed at any time and at any intensity of the input optical radiation by by passing a current through the control electrode.

Photoresistive PVCs with external optical control

Similarly to PVC with external electrical control, the population of the levels of a multiply charged impurity can be changed by additional optical radiation *M* (Figure 6). Switching between sensitivity subranges requires some threshold intensity of optical radiation *M* [5, 9]. The switching process is similar to that implemented in the previous device structures, and also occurs in a time determined by the lifetime constant of charge carriers. Since the processes of changes in the level population and carrier lifetime constants (1) do not depend on the physical nature of the cause of change in the level population, it is possible to implement combined optoelectronic control in one PVC device structure (Figure 6*b*).

Another device structure that makes it possible to significantly expand the range of realized parameters values by the use of the combined technology is a structure based on several semiconductor materials epitaxially grown on a common sapphire substrate.

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Close values of a number of sapphire′s and many semiconductor materials` parameters (crystal lattice constant, thermal expansion coefficients) make it possible to fabricate device structures based on dissimilar materials [10–13]. Figure 7 shows the basic device structure of a photovoltaic converter based on semiconductor 1 with a deep multiply charged

impurity which characteristics are controlled by optical radiation M generated by light-emitting diode 4–5. In this case the input optical signal S can be led into the PVC structure both from the side of the semiconductor layers S_1, and through the substrate (S_2) since sapphire is also characterized by excellent optical properties in the near and middle IR optical range.
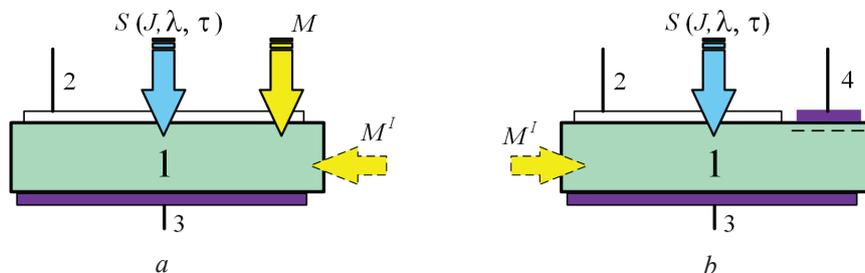

Figure 6 – Device structure of the PVC with external optical (*a*) and combined (*b*) control
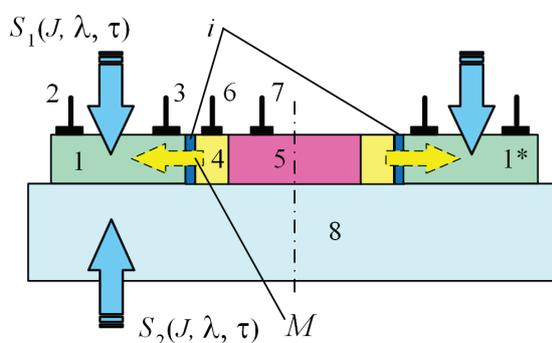

Figure 7 – Device structure that combines PVC structure with external optical control and a controlling light-emitting diode: 1 – PVC; 2, 3 – PVC contacts; 4–5 – light-emitting diode; 6, 7 – light-emitting diode contacts; 8 – sapphire substrate; S – measured optical signal; M – controlling optical signal; i – insulating immersion layer

Such a structure (Figure 7) allows combining the technologies of light-emitting devices based

on semiconductor compounds A^3B^5, photodetector structures based on Si, Ge, Si: Ge and other materials, integral structures of amplifier and signal processing circuits and also "Non-Silicon" technologies on one substrate [12, 13]. This structure can also serve as a basis for designing functional PVCs.

PVC with internal amplification

In the PVC device structure shown on Figure 8 the main electrodes form Schottky barriers and a PVC itself is essentially a diode structure with a long base and a two oppositely connected Schottky diodes. When using barrier structures as PVC, optical modulation of the Schottky barrier height produces the effect of internal photocurrent multiplication [9, 14], which occurs at forward bias, in contrast to classic avalanche and other devices operating at reverse bias, and therefore at high bias voltages.
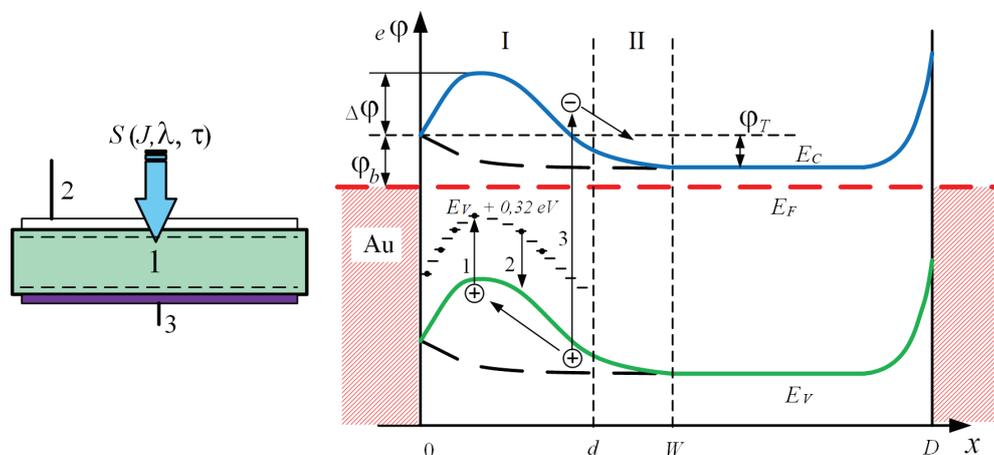

Figure 8 – Structure of a two-barrier photodetector with internal amplification in region I

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Besides that a PVC design with oppositely connected barrier structures implements spectral response characteristic with a photovoltage sign inversion [5, 9]. In this case single-element two-barrier PVCs allow to measure the intensity of optical radiation with simultaneous determination of optical radiation wavelength just by changing the power supply mode of the photodetector without necessity to use any optical dispersing elements which greatly simplifies the design of the measuring transducer.

Functional PVCs

Forming the variety of single-element PVC characteristics (Figures 2, 4–8) not due to the complexity of the device structure, but due to the use of peculiar features of the multistage physical processes of recharging various deep impurities levels makes it possible to build multifunctional sensors that utilize basic single-element PVC designs just by changing electrode configurations and bias feed schemes [5, 8–9].

The principle of position-sensitive photodetector (Figure 10) is based on the use of the lateral photovoltage measuring signal to determine the X and Y coordinates of the light spot and the position of the focused light spot to determine the Z coordinate [9]. The device structure has 5 contacts to get signals on X and Y coordinates and 2 contacts to form signal on Z coordinate of the light spot of object image. Photovoltage indices on PVC conversion characteristics correspond to structure's contact numbers.

Physical processes that determine the dependence of the lateral photovoltage between contacts 3–3* on the depth of the focused image also lead to photovoltage sign inversion on a spectral curve (Figure 9).
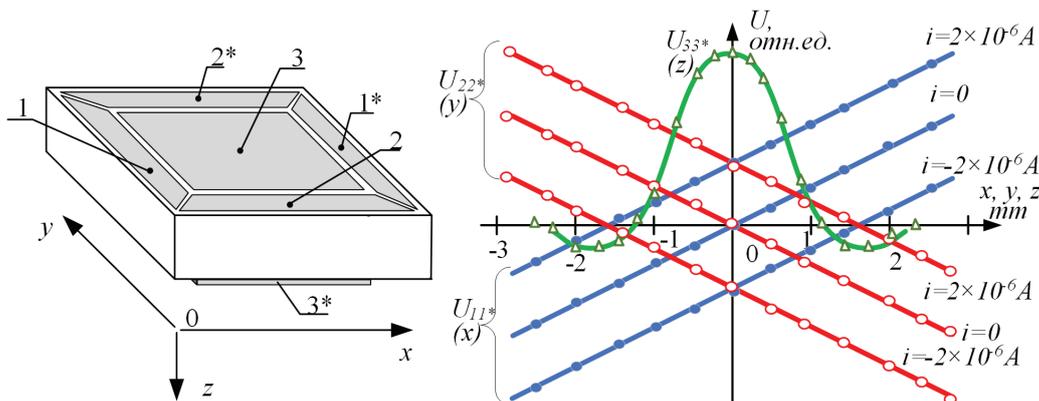

Figure 9 – Structure of a three-coordinate position-sensitive PVC and its characteristics
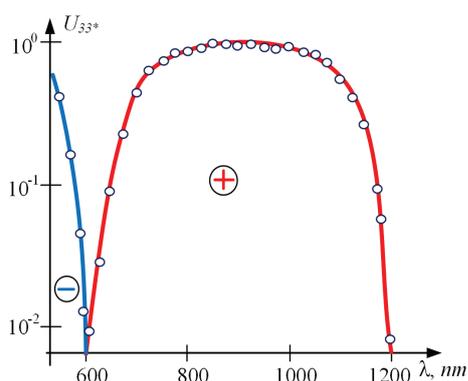

Figure 10 – Spectral characteristic of a three-coordinate position-sensitive PVC

PVC structure based on semiconductor with intrinsic photoconductivity that is shown on Figure 11 acts an optical comparator comparing two optical signals by such parameters as: optical radiation intensity, monochromatic radiation wavelength, position and shape of the optical spot [5, 9] of optical signals S_1 and S_2 applied to different sides A and B of a single-element functional PVC.
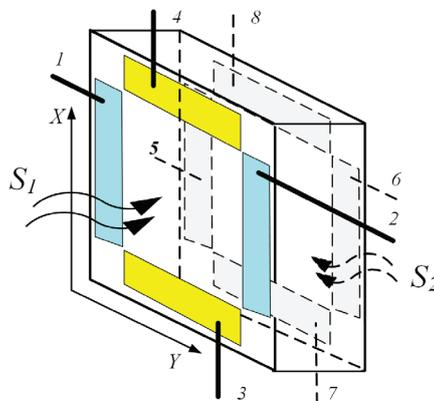

Figure 11 – Optoelectronic comparator based on single-element two-barrier coordinate-sensitive PVC

Since ionization of deep impurity with several energy levels for different charge states can occur under the influence of various factors, it is possible to design functional PVCs sensitive to input influences of various physical nature [4–5, 9] on a basis of given structures range of PVCs based on semiconductors with intrinsic photoconductivity. PVC performance could be Improved or modified by various technological methods, e. g. profiling the surface of the PVC to reduce the optical reflection coefficient.

Conclusion

Here was shown that device structures based on semiconductors with low concentration of deep impurity slightly doped with deep impurities forming several levels with different charge states within semiconductor′s bandgap could be used to create photovoltaic converters with different functionality using basic device structures range.

Analysis of conversion characteristics peculiarities of single-element photovoltaic converters based on semiconductors with intrinsic photoconductivity and systematization of their performance and structures makes it possible to represent possible PVC structures range as following:

– PVCs with internal control;

– Photoresistive PVCs with external electrical control;

– Photoresistive PVCs with external optical control;

– PVCs with combined control;

– PVCs with internal amplification;

– Functional PVCs.

Using structures range of single-element PVC based on a semiconductor with intrinsic photoconductivity in measurement transducers for optical diagnostics provides measurement of both optical radiation parameters (intensity, wavelength) with automatic or controlled switching between measurement subranges and other physical quantities for functional PVCs.

Examples of constructing functional PVCs using a basic device structures range of single-element PVCs based on a semiconductor with intrinsic photoconductivity are shown.

References

1. Lysenko S.A. *Metody opticheskoj diagnostiki biologicheskikh ob″ektov* [Methods for Optical Diagnostics of Biological Objects]. Minsk: BGU Publ., 2014, 231 p.

2. Filachev A.M., Taubkin I.I., Trishenkov M.A. *Fotopriemniki v optiko-ehlektronnykh priborakh i sistemakh* [Photodetectors in Optoelectronic Devices and Systems]. Moscow: Fizmatkniga Publ., 2016, 104 p.

3. Formozov B.N. *Aehrokosmicheskie fotopriemnye ustrojstva v vidimom i infrakrasnom diapazonakh* [Aerospace Photodetectors in the Visible and Infrared Ranges]. St. Petersburg: SPbGUAP Publ., 2002, 120 p.

4. Gusev O.K., Vorobey R.I., Zharin A.L., Svistun A.I., Tyavlovsky A.K., Tyavlovsky K.L. *Metodologiya i sredstva izmerenij parametrov ob″ektov s neopredelennymi sostoyaniyami* [Methodology and Tools for Measuring Parameters of Objects in Uncertain States], ed. O.K. Gusev. Minsk: BNTU Publ., 2010, 582 p.

5. Vorobey R.I., Gusev O.K., Tyavlovsky A.K., Tyavlovsky K.L., Svistun A.I., Shadurskaya L.I., Yarzhembitskaya N.V., Kierczynski K. Photoelectric semiconductor converters with a large dynamic range. *Przeglad electrotechniczny*, 2014, no. 5, pp. 5–78.
DOI: 10.12915/pe.2014.05.16

6. Bondar I.V., Rud V.Yu., Rud Yu.V. [Photovoltaic Effects in Cu(Al, In) /p-CuIn$_3$Se$_5$ Schottky Barriers]. *Fizika i tekhnika poluprovodnikov* [Semiconductor Physics and Technology], 2007, vol. 41, no. 1, pp. 44–47 (in Russian).

7. Yashin A.N. [Applicability of the simplified Shockley-Reed-Hall model for semiconductors with various types of defects]. *Fizika i tekhnika poluprovodnikov* [Semiconductor Physics and Technology], 2005, vol. 39, no. 11, pp. 1331–1335. (in Russian).

8. Masol I.V., Osinsky V.I., Sergeev O.T. *Informatsionnye nanotekhnologii* [Informational Nanotechology]. Kiev: Makros Publ., 2011, 560 p.

9. Gusev O.K., Tyavlovsky K.L., Vorobey R.I., Svistun A.I., Shadurskaya L.I. [Intrinsic Semiconductor-Based Photodetectors for Measurement Transducers Construction]. *Metrologiya i priborostroyeniye* [Metrology and Instrument Engineering], 2017, no. 2, pp. 34–42 (in Russian).

10. Andreou A.G., Kalayjian Z.K., Apsel A., Pouliquen P.O., Athale R.A., Simonis G., Reedy R. Silicon on sapphire CMOS for optoelectronic microsystems. Circuits and Systems, 2001, vol. 1, pp. 22–30.
DOI: 10.1109/7384.963464

11. Kozlov Yu.F., Zotov V.V. *Struktury kremniya na sapfire: tekhnologiya, svojstva, metody kontrolya, primenenie* [Silicon on Sapphire structures: Technology, Properties, Methods of Control, Applications]. Moscow: MIET Publ., 2004, 380 p.

12. Vityaz P.A., Svidunovich N.A., Kuis D.V. *Nanomaterialovedenie* [Nanomaterials Science]. Minsk: Vysheyshaya Shkola Publ., 2015, 511 p.

13. Wado H., Ohtani K., Ishida M. Epitaxial growth of SiGe on Al_2O_3 using Si_2H_6 gas and Ge solid source molecular beam epitaxy. *J.Crystl.Growth*, 1996, vol. 169, pp. 457–462. **DOI:** 10.1016/S0022-0248(97)80004-8

14. Khudaverdyan S.Kh. Photo-detecting characteristics of double barrier structures. *Nuclear Inst. and Methods in Physics Research A.*, 2003, vol. 504, iss. 1–3, pp. 350–353.
DOI: 10.1016/S0168-9002(03)00768-X