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Determination of the resistance of external parameters to the degradation of the parameters of silicon photocells with input nickel atoms

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Currently, there is a growing need for high-performance photocells with increased stability of parameters to external influences, such as thermal and radiation resistance. This work is devoted to the study of photocells available in the volume of an ordered micro- and nanostructure based on silicon doped with impurity nickel atoms. The study of the formation of micro- and nanoclusters of impurity atoms in silicon photocells that were subjected to additional high-temperature processing makes it possible to determine the degradation of nickel clusters, which strongly affect the electrical parameters of photocells. It is shown that impurity nickel atoms will increase the stability of the electrophysical parameters of photocells under the influence of both high temperature and radiation. The results obtained in the study showed that the introduction of nickel impurity atoms into the volume of silicon-based photocells leads to temperature and radiation resistance, and also increases efficiency.

Key words: cluster, nickel, degradation, diffusion, photocell, self-organization, semiconductor, doping, supersaturation factor, solubility, low-temperature annealing.
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1 Introduction

One of the new and promising methods for creating nanosized structures in the crystal lattice of a semiconductor is the formation of nanoclusters of impurity atoms with the participation of uncontrolled defects in the crystal lattice, since this method of creating nanosized structures, in contrast to the existing methods of molecular beam epitaxy, which require complex expensive equipment, has the following advantages [1, 2]:

– allows one to create nanoscale structures evenly distributed throughout the volume of the crystal;

– makes it easy to control the structure, composition, distribution of nanoscale structures and their ordering;

– this method can be used to obtain a material with stable electrophysical parameters and external influences, such as temperature and radiation [1, 3];

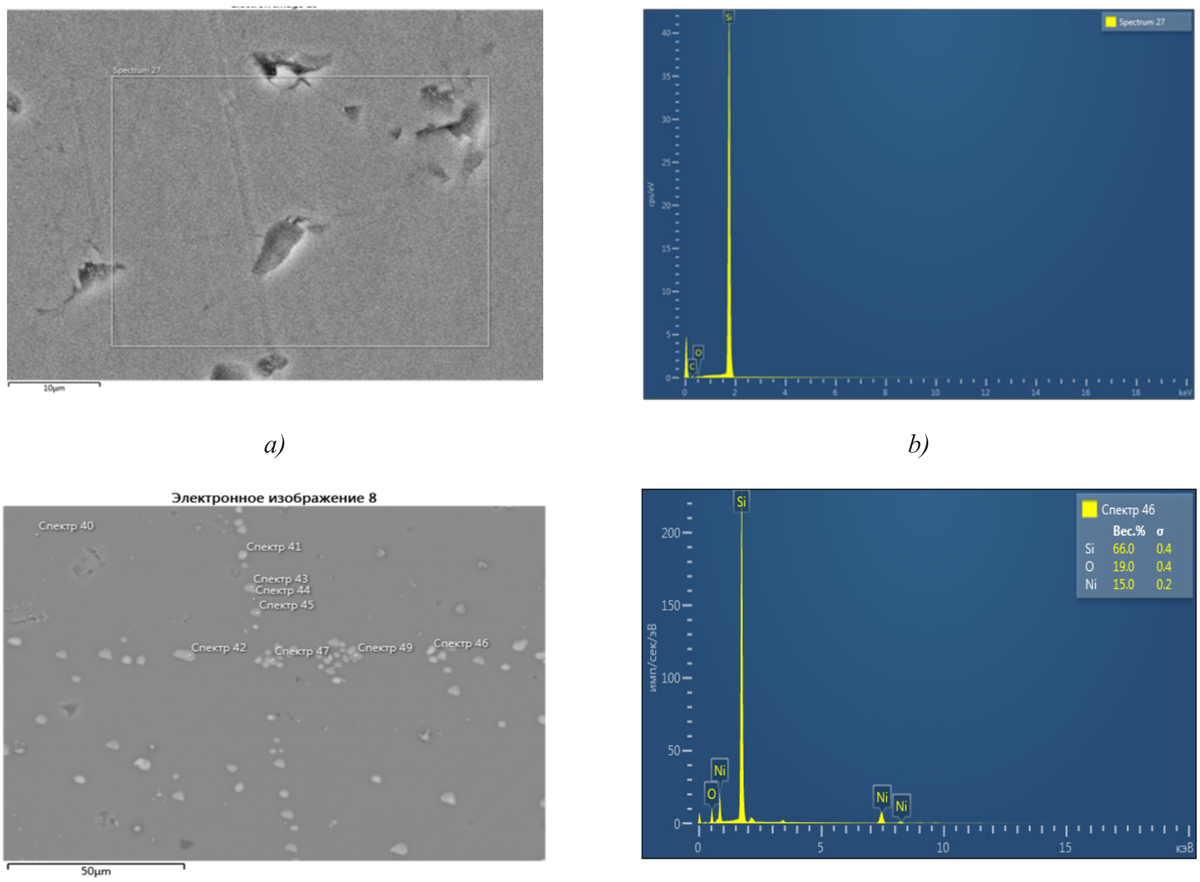
– allows you to control the charge state of nanoclusters in a wide range (N+(-)n, where n>3), that is, to create multiply charged centers in a semiconductor, which are the basis for a very promising material for nanophotonics [4-7].

This paper presents original experimental results on the study of the electrical and photoelectric properties of photovoltaic cells based on silicon with nanoclusters of impurity nickel atoms. Investigation of the influence of high-temperature processing and the influence of radiation γ – irradiation on the electrophysical parameters of the obtained photocells. It is shown that such a study significantly increases the possibility of large-scale use of photocells based on silicon doped with impurity nickel atoms under extreme conditions and also increases the efficiency of their operation.

Therefore, the main goal of this work is to show that under certain conditions of doping with impurity nickel atoms, nanoclusters are formed and to show the possibility of controlling the size and distribution of clusters in silicon.

2 Technology for obtaining materials and research method

Recently, specialists in the field of nanotechnology and nanoelectronics have paid great attention to the technology of obtaining self-organizing impurity clusters with controlled structures [8–11]. In this regard, some interesting results on the implantation of Co and Ge ions in Si, as well as on the ion implantation of other atoms in semiconductor materials, should be noted [12–17]. As far as we know, technologies for obtaining self-organizing clusters of impurity atoms using diffusion technologies have not been sufficiently studied at present. And the diffusion technology for obtaining nanosized structures is not only a more accessible and cheap method that allows large-scale production, but also makes it possible to create nanosized structures of various types and a given distribution and density over the volume of the crystal.



a) *b)*

c) d)

Figure 1 – Pictures of the surfaces of photovoltaic cells with nickel clusters (REM):
a) – Control sample surface without clusters; b) – spectrum without cluster zones;
c) – with cluster zones at Ni = 9.5%; d) – with cluster zones at Ni = 15%.

Using an EVOMA-10 electron microscope, the surface of polished photocells was examined at a certain temperature. Figure 6 shows a structural analysis of photocell plates with impurity nickel atoms, which were obtained using an electron microscope of the brand Oxford Instruments ZEISS EVOMA-10.

The obtained results prove that in photocells there are clusters of impurity nickel atoms in the range of 9–15%, while the experimental error was within the error of σ=0.1–0.2%.

3 Experimental results and their discussion

The stability of the electrophysical parameters of the obtained photocells, when operating under experimental conditions such as elevated temperatures and relatively high radiation intensities, leading to the formation of various defects, which lead to a strong change in the parameters of the base material. This is due to the fact that during high-temperature operations, the concentration and size of clusters that form impurity nickel atoms change. To elucidate the nature of the change in the electrophysical parameters of photocells based on silicon doped with impurity nickel atoms into silicon, studies were carried out on the effect of additional thermal annealing on the open circuit voltage and short circuit current of control photocells [18–20].

The study of the effect of additional high-temperature annealing after the formation of a p-n junction led to a decrease in the initial parameters of photocells. The short-circuit current and open-circuit voltage of photocells depended quite strongly on the characteristics of the initial structures of photocells (the depth of the p-n junction, the doping concentration of the frontal and base regions). It was found that the higher the temperature and time of additional high-temperature annealing, the stronger the decrease in the initial $U_{o.c.v.}$ and $I_{sh.c.c.}$, and the degradation is more pronounced in the case of a shallow (less than 1 μm) p-n junction. For a photocell with a deep p-n junction, the change in the initial parameters was less pronounced [21-24]. Tables 1 and 2 show data on the change in the open circuit voltage and short circuit current of the control photocell depending on the temperature of thermal annealing at an annealing time of 1 hour. Table 1 shows the data for the starting material SEC-0.5.

Table 1 – Changes in the open-circuit voltage and short-circuit current of control photocells based on SEC-0.5 depending on the temperature of thermal annealing at an annealing time of 1 hour

Depth p-n, microns	Options	Annealing temperature, °C.				
		Initial	900	1000	1100	1200
0,5	U_{xx}, mV	527	491	439	402	374
	$J_{кз}$, mA	16,8	14,2	12,8	11,6	10,7
1	U_{xx}, mV	595	572	546	514	497
	$J_{кз}$, mA	20,5	18,5	17,5	16,6	15,8
3	U_{xx}, mV	588	568	552	534	514
	$J_{кз}$, mA	17,3	15,6	14,8	14,1	13,5

The study of the effect of additional heat treatment on the parameters of photocells with clusters of impurity nickel atoms at T = 600 and 650 °C for 3 hours showed that no practical changes were observed in the electrophysical parameters of photocells. In the control samples after heating at T = 600 °C, a decrease in the short-circuit current by 3-6% of the initial value was observed [25-27]. During heat treatment of photocells doped with nickel atoms, a decrease in the initial values of $I_{sh.c.c.}$ was observed. and $U_{o.c.v}$. After heat treatment, an increase in $I_{sh.c.c}$ and $U_{o.c.v}$ was observed in some photocells. This connection was more pronounced in photocells having a low dopant concentration with the formation of low energy levels. For example, on heat-treated photocells, impurities in the original silicon (boron or phosphorus), which form small energy levels, go into the compensation position [28-31]. As a result of interaction with impurities that form deep energy levels, the values of $U_{o.c.v.}$ and $I_{sh.c.c}$. photocells drop to zero.

After the formation of the p–n junction, a decrease in the parameters of additionally heat-treated photocells was observed. If the heat treatment time was longer, then this sharply reduced the initial values of $U_{o.c.v.}$ and $I_{sh.c.c}$.

Tables 2 and 3 provide information on the change in open circuit voltage and short circuit current depending on heat treatment for 1 hour. Table 2 shows the data on the initial starting material PhES -4.5. Table 3 shows the electrophysical parameters of photocells made of PhES-40 silicon. Additional heat treatment time 1 hour.

Table 4 shows the electrophysical parameters of photocells made on SEC-10 grade silicon. Additional heat treatment time 1 hour.

Table 5 shows the electrophysical parameters of photocells made on the basis of SEC-0.5 silicon and subjected to additional heat treatment t=1 hour.

Table 2 – Data obtained for photocells based on PhES-4.5 silicon

Additional heat treatment temperature, °C	Average cluster sizes, microns	$U_{o.c.v}$, mV	$I_{sh.c.c.}$, mA/cm^2
1200	1-2	514	13,5
1100	1,5-2	534	14,1
1000	2,5-3	552	14,8
900	1,5-2	568	15,6
Control sample	-	588	17,3

Table 3 – Electrophysical parameters of photocells made on the basis of silicon grade PhES-40

Additional heat treatment temperature, °C	Average cluster sizes, microns	$U_{o.c.v}$, mV	$I_{sh.c.c.}$, mA/cm^2
1200	1 – 2	374	10,7
1100	2 – 5	402	11,6
1000	2 – 7	439	12,8
900	2 – 8	491	14,2
Control sample	-	527	16,8

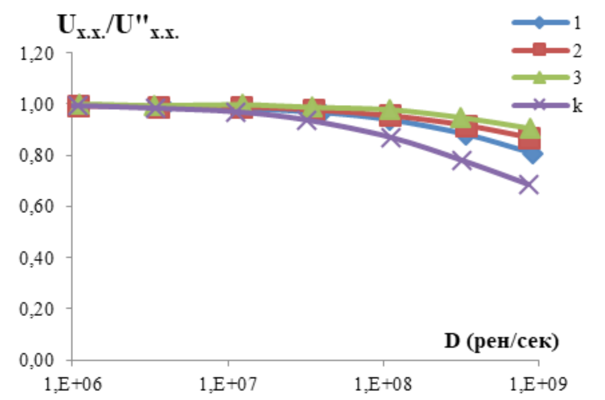
Table 4 – Electrophysical parameters of photocells made on the basis of SEC -10 silicon

Additional heat treatment temperature, °C	Average cluster sizes, microns	$U_{o.c.v}$, mV	$I_{sh.c.c}$, mA/cm^2
1200	1 – 2	497	15,8
1100	2 – 5	514	16,6
1000	2 – 5	546	17,5
900	2 – 20	572	18,5
Control sample	-	595	20,5

Table 5 – Electrophysical parameters of photocells made on the basis of silicon grade SEC -0.5

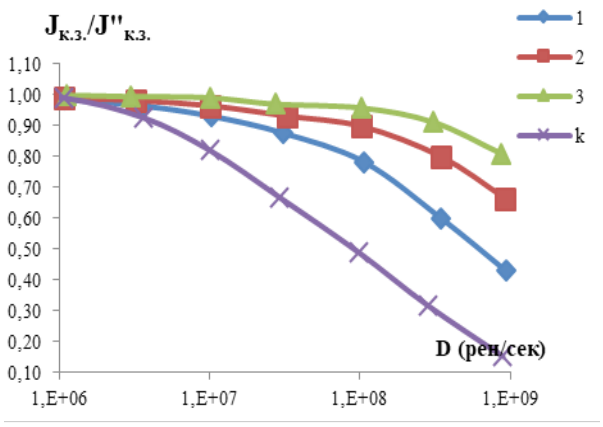
Additional heat treatment temperature, °C	Average cluster sizes, microns	$U_{o.c.v}$, mV	$I_{sh.c.c}$, mA/cm^2
1100	0,5 – 1	480	20,9
1000	1 – 1,5	482	21,4
900	1,5 – 2,5	498	45,7
800	2,5 – 3	506	28,1
Control sample	0,5 – 1	507	20,5

The study of the effect of γ-radiation was carried out in the range of irradiation doses from 10^5 to 10^9 R/sec on the electrical parameters of photocells based on silicon with clusters of nickel atoms. Figures 2 and 3 show the results of studying the dependences of the short-circuit current and open-circuit voltage on the dose of γ-radiation.



1, 2, 3 – concentration of nickel atoms respectively Ni 10^{15} cm^{-3}, 10^{16} cm^{-3}, 6×10^{16} cm^{-3}, j – control photocell.

Figure 2 – Change in open circuit voltage of photocells



1, 2, 3 – concentration of nickel atoms respectively Ni 10^{15} cm^{-3}, 10^{16} cm^{-3}, 6×10^{16} cm^{-3}, j – control photocell.

Figure 3 – Change in the short circuit current of photocells

The dependence of the open-circuit voltage of photocells on the dose of γ-radiation is shown in Figure 2. Here the concentration of nickel impurity atoms was respectively equal to: 1 – 1×10^{15} cm^{-3}, 2 – 1×10^{15} cm^{-3}; 3 – 6×10^{16} cm^{-3}, j – for the control sample with no impurity of nickel. Such dependences were obtained in the study of changes in the short circuit current on the dose of γ radiation (Fig. 3).

After irradiation of photocells additionally doped with nickel atoms with an optimal concentration of γ-radiation with a dose of 10^9 R, the open circuit voltage drops by 8–10% relative to non-irradiated samples. In the same samples, the short-circuit current decreased by 15–18%. Under the same conditions, the degradation of the parameters of the control photocells subjected to irradiation amounted to 25–30% in voltage and 70–80% in current. When irradiated with gamma rays with a dose of up to 10^9 R, the electrophysical parameters of photocells with introduced nickel atoms did not exceed 5 and 10%, respectively.

When irradiated with a dose of up to 10^7 R, the change in the values of the open-circuit voltage and short-circuit current was no higher than 1–2%.

4 Conclusions

The uniqueness of silicon-based solar cells with nanoclusters of nickel atoms lies in the fact that the electrophysical parameters are thermally stable and radiation resistant, which play an important role in solar node operation. Based on the results of the data obtained, the following important conclusion can be drawn – the radiation stability of photocells additionally alloyed with nickel atoms improves the open-circuit voltage and short-circuit current by two to four times relative to the parameters of control photocells made without impurity nickel atoms. This shows that the introduction of impurity nickel atoms into silicon leads to thermal stability and radiation resistance, which lead to an increase in the efficiency of photocells.

Silicon-based solar cells with nanoclusters of nickel atoms have unique functionality in the field of modern photovoltaics.

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