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Comparative study of photocells based on silicon doped with nickel by various methods

© K.A. Ismailov[1], N.F. Zikrillaev[2], S.V. Koveshnikov[2], E.Zh. Kosbergenov[1,¶]

[1] Berdakh Karakalpak State University,
230112 Nukus, Uzbekistan
[2] Tashkent State Technical University,
100095 Tashkent, Uzbekistan
¶ E-mail: ernazar.kosbergenov@gmail.com

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In this work, the parameters of silicon-based photocells doped with impurity nickel atoms by diffusion methods and during growth were compared. It was found that photocells doped with impurity nickel atoms during silicon growth have an improvement in parameters comparable to that obtained by the diffusion doping method. Additional heat treatment at $T = 800^\circ$C makes it possible to significantly improve their basic parameters.

Keywords:silicon, photocell, nickel, thermal annealing, diffusion.

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1. Introduction

To improve the efficiency of silicon-based photocells, various methods are used. One of the methods is gettering of impurities, which worsen the lifetime of auxiliary charge carriers [1–4]. It was shown [5–8], that by forming nickel atoms clusters in the silicon lattice, gettering of various rapidly diffusing and uncontrollable impurities is possible.

The studies [9–13] showed, that doping of a silicon-based photocell with impurity nickel atoms by diffusion method leads to an improvement in its efficiency due to the gettering properties of nickel clusters. However this method (diffusion doping of silicon with nickel) to improve the photocell parameters requires several technological operations, such as chemical cleaning before and after nickel diffusion, nickel spraying (or nickel chemical deposition), diffusion annealing, etc. [5,7,9].

In this regard, the study of the photocell based on silicon doped with nickel at crystal growing deserves attention. The purpose of this study was to compare the parameters of the photocell based on silicon doped with nickel by diffusion methods and when growing.

2. Experimental results and discussion

The Figure shows the technological scheme for obtaining photocell test samples. Silicon wafers of three groups were used as the starting material for photocell manufacture.

– Group 1 (Si) — silicon (no nickel) — of type with specific resistivity $\rho \sim 40\,\mathrm{Ohm \cdot cm}$ (KDB-40).

– Group 2 (Si_{diff}) — silicon doped with nickel by diffusion technology. For this a layer of pure nickel with a thickness of $1\,\mu$m was deposited in vacuum on the surface of silicon samples (with the same parameters as for group 1 samples), and nickel was diffused at the optimum temperature $T = 850^\circ$C, within $t = 30$ min [8].

– Group 3 (Si_{growth}) — silicon doped with nickel in the process of growing, *p*-type with specific resistivity $\rho \sim 70\,\mathrm{Ohm \cdot cm}$ (KDB-70).

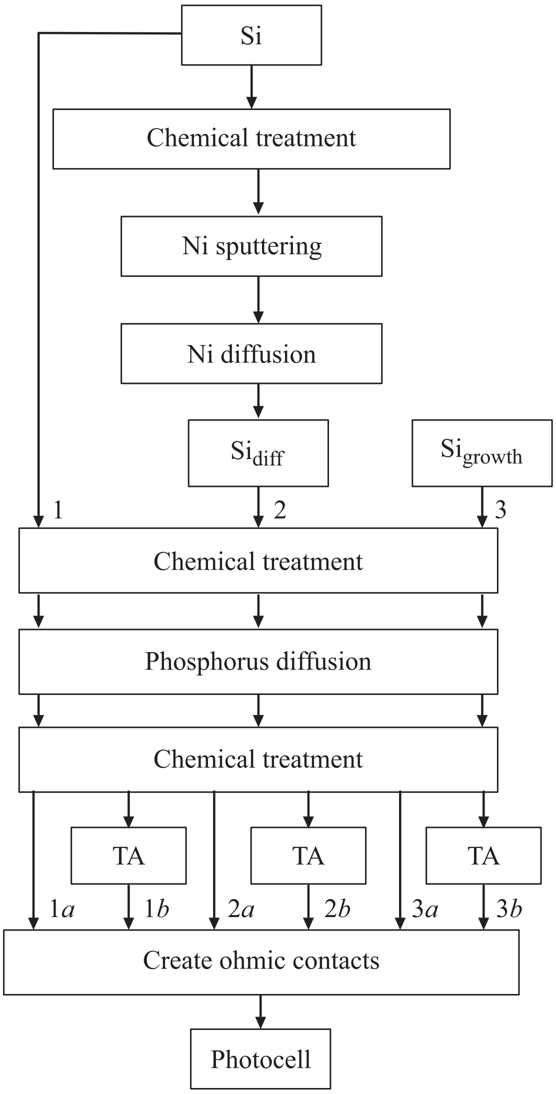
The parameters of the initial samples of all three groups, measured by the Hall effect method, are shown in Table 1. The Table 1 shows, that samples parameters do not differ significantly from each other.

Prior phosphorus diffusion the samples of all groups of sizes $0.8 \times 5 \times 10$ mm were subjected to chemical cleaning (in 10% HCl, then in 10% HF). Phosphorus diffusion was at $T = 1000^\circ$C for $t = 30$ min, while the *p*-transition depth was $0.6-0.8\,\mu$m. In the samples of the 2nd group, phosphorus was diffused to the sample „nickel" side. After diffusion each group of samples was divided into two subgroups (subgroups *1a*, *1b*; *2a*, *2b*; *3a, 3b*), and *b* subgroup samples were additionally annealed (stage „TA" — Thermal annealing) at $T = 800^\circ$C for $t = 30$ min to activate the processes of gettering with nickel clusters [8].

Once ohmic contacts were created, photocell CVC were measured and photocell parameters of the subgroup „*a*" were determined (Table. 2). According to photocell CVC, the average values of photocell parameters and their

Table 1. Starting materials parameters for samples of 1, 2 and 3 groups

Group	Type conductivity	Concentration p, cm^{-3}	Hall mobility μ, cm^2/(V·s)
Group 1 (Si)	p	$4.7 \cdot 10^{14}$	320
Group 2 (Si_{diff})	p	$4.7 \cdot 10^{14}$	335
Group 3 (Si_{growth})	p	$2.8 \cdot 10^{14}$	310



Technological scheme for obtaining photocell test samples.

relative changes were determined: V_{oc} — no-load voltage; $(V_{oc}-V_{oc1})/V_{oc1}$ —relative change in no-load voltage (relative to the average value for the samples of group $1a$); J_{sc} — short circuit current density;$(J_{sc}-J_{sc1})/J_{sc1}$ — the change in short circuit current density (relative to the average value for the samples of group $1a$); P_{peak} — specific peak power (calculated as the product of J_{sc} and V_{oc}); $(P_{\text{peak}}-P_{\text{peak1}})/P_{\text{peak1}}$ –relative change in specific peak power (relative to the average value for the samples of group $1a$).

Photocell parameters were rather low due high base volume resistivity [14] and large sample thicknesses [15,16].

As it is seen in the Table 2, in the samples of group $2a$ the value V_{oc} increases by 5.3% (relative to the average value V_{oc} of group $1a$), and value J_{sc} increases more noticeably — by 7%, i.e. considerable photocell improvement is observed. In the samples of group $3a$ the average value V_{oc} relative to the same value for group $1a$ increases by 6.1%, and J_{sc} — by 4.7%.

Table 2. Average values of photocell parameters for samples of the subgroup „*a*“ and their relative changes

Group	$1a$	$2a$	$3a$
V_{oc}, mV	377	397	400
$(V_{oc}-V_{oc1})/V_{oc1}$, %	–	5.3	6.1
J_{sc}, mA/cm^2	17	18.2	17.8
$(J_{sc}-J_{sc1})/J_{sc1}$, %	–	7	4.7
P_{peak}, mW/cm^2	6.4	7.2	7.1
$(P_{\text{peak}}-P_{\text{peak1}})/P_{\text{peak1}}$, %	–	12.5	10.9

Table 3. Average values of photocell parameters for samples of the subgroup „*b*“ and their relative changes

Group	$1b$	$2b$	$3b$
V_{oc}, mV	383	412	423
$(V_{oc}-V_{oc.a})/V_{oc.a}$, %	1.6	3.8	5.7
J_{sc}, mA/cm^2	17.5	19.7	19.3
$(J_{sc}-J_{sc.a})/J_{sc.a}$, %	3	8.2	8.4
P_{peak}, mW/cm^2	6.7	8.1	8.2
$(P_{\text{peak}}-P_{\text{peak}.a})/P_{\text{peak}.a}$, %	4.7	12.5	15.5

Based on the results obtained, we can state, that doping with nickel impurity atoms while growing silicon leads to the improvement of photocell parameters V_{oc} and J_{sc} compared the diffusion doping method. Further improvement photocell parameters due to the gettering activation requires additional thermal annealing. In this case, the recombination impurity atom should release the site state in the silicon lattice, then it should diffuse to the getter surface, and, finally, it should be captured by the getter [3,4].

Table 3 demonstrates main photocell parameters of the group „*b*“: V_{oc} — no-load voltage; $(V_{oc}-V_{oc.a})/V_{oc.a}$ — relative change in no-load voltage (relative to the average value for the samples of subgroup „*a*“); J_{sc} — short circuit current density;$(J_{sc}-J_{sc.a})/J_{sc.a}$ — the change in short circuit current density (relative to the average value for samples of group „*a*“); P_{peak} — specific peak power; $(P_{\text{peak}}-P_{\text{peak}.a})/P_{\text{peak}.a}$ — relative change in specific peak power (relative to the average value for the samples of subgroup „*a*“).

As it is seen in the Table 3, the parameters of $1b$ group samples after annealing also increased compared to $1a$ group samples. This can be explained by gettering phosphorus properties [17]. Group $2b$ samples properties changed significantly towards improvement. At the same time J_{sc} increases compared the group $2a$ samples by 8.2%, and V_{oc} — by 3.8%. Growth of group $2b$ photocell peak power relative to $1b$ (control) was 21%. Very good results were obtained for group $3b$ samples: value J_{sc} increases compared to group $3a$ samples by 8.4%, and the value V_{oc} grows by 5.7%. Growth of group $3b$ photocell peak power relative to group 1b (control) was 22%. This shows that the diffusion method of doping with nickel is less efficient compared to the alloying while growing.

3. Conclusion

It was found, that in the photocell doped with impurity nickel atoms during silicon growing with further additional heat treatment, there is a noticeable (up to 22% in power) improvement in their main parameters.

Doping of silicon with nickel during crystal growing allows to obtain large ingots of single-crystal silicon, uniformly doped with nickel throughout the volume, without additional operations and costs. This technology opens up new possibilities for the creation of low-cost silicon photocells with increased efficiency.

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Conflict of interest

The authors declare that they have no conflict of interest.

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