HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

UDC 621.315.592:546.28

EFFECT OF VARIOUS METAL IMPURITIES ON RECOMBINATION PHENOMENA IN SILICON

Esonboyev Farruxbek

Andijan State University

Doi: https://doi.org/10.5281/zenodo.23229212

Abstract. This article analyzes Shockley-Read-Hall recombination in silicon caused by metal impurities present as point defects, metal-acceptor pairs, silicide precipitates, and metal-decorated dislocations. The study is based on a systematic review covering English- and Russian-language sources published from 1952 to 2025 with DOIs or stable bibliographic records, as well as experimental results reported by researchers from Uzbekistan. Comparison of SRH parameters shows that the electron-capture cross section at Fe_i, V_i, Ti_i, and Mo_i centers is substantially larger than the hole-capture cross section. Therefore, under low-injection conditions, these centers are particularly detrimental to p-type silicon. Substitutional acceptor centers such as Au have a stronger effect in n-type material. The influence of Cu, Ni, and Co depends more strongly on their precipitation and decoration of extended defects than on the concentration of dissolved atoms. The results demonstrate that, in addition to the metal species, its chemical state, spatial location, injection level, and thermal history must also be controlled.

Keywords: silicon; recombination; metal impurity; carrier lifetime; Shockley-Read-Hall center; gettering; iron; nickel.

Abstract. The article analyzes Shockley-Read-Hall recombination in silicon caused by metallic impurities occurring as point defects, metal-acceptor pairs, silicide precipitates, and decorated dislocations. The work was carried out as a systematic review of English- and Russian-language publications from 1952 to 2025 with DOIs or stable bibliographic records, including experimental studies by researchers from Uzbekistan. Comparison of SRH parameters shows that, for Fe_i, V_i, Ti_i, and Mo centers, the electron-capture cross section substantially exceeds the hole-capture cross section; therefore, at low injection levels they are especially harmful to p-type silicon. Substitutional acceptor centers, particularly Au, more strongly limit lifetime in n-type material. The effects of Cu, Ni, and Co are determined mainly by precipitation and decoration of extended defects. It is concluded that the chemical state, spatial distribution, injection level, and thermal history of an impurity must be considered simultaneously.

Keywords: silicon; recombination; metallic impurity; carrier lifetime; Shockley-Read-Hall center; gettering; iron; nickel.

Abstract. This article analyses Shockley-Read-Hall recombination in silicon caused by metallic impurities present as point defects, metal-acceptor pairs, silicide precipitates, and decorated extended

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

defects. The study is a systematic review of English- and Russian-language publications from 1952 to 2025 with DOIs or stable bibliographic records, including experimental work by researchers from Uzbekistan. Comparison of SRH parameters shows that Fe_i, V_i, Ti_i, and Mo centers have electron-capture cross sections substantially larger than their hole-capture cross sections; they are therefore particularly harmful in low-injection p-type silicon. Substitutional acceptor centers such as Au have a stronger lifetime impact in n-type material. For Cu, Ni, and Co, precipitation and decoration of extended defects often dominate over isolated dissolved atoms. The review demonstrates that impurity species alone is an insufficient predictor: chemical state, spatial distribution, injection level, conductivity type, and thermal history must be considered together.

Keywords: silicon; recombination; metal impurity; carrier lifetime; Shockley-Read-Hall center; gettering; iron; nickel.

1 INTRODUCTION

The performance of crystalline silicon in electronic and photoelectric devices is directly related to the lifetime of nonequilibrium electron-hole pairs. The longer a carrier survives before recombination, the greater its diffusion length and the higher the probability that it will be collected by a p-n junction or a selective contact. In pure, well-passivated silicon, radiative and Auger recombination set the fundamental limit; in real technological materials, however, deep energy levels created by metal atoms often make SRH recombination dominant. [2-4]

Transition metals may enter silicon from the raw material, crucible and thermal-field components, cutting and polishing operations, the diffusion furnace, metallization, or the processing environment. Their hazard is not determined by concentration alone. The same element may exhibit different recombination activity as an interstitial atom, substitutional atom, dopant pair, nanocluster, silicide precipitate, or phase segregated at grain boundaries. Although Fe, Ni, Co, Mo, and Cr have been detected in multicrystalline silicon in the range of 10^{12}-10^{16} cm^{-3}, the measured diffusion length was substantially greater than the value calculated for the case in which all atoms were dissolved active centers. This indicates that a significant fraction of these metals is present as clusters or precipitates and is distributed nonuniformly in space. [8,11]

The practical aspect of the problem combines two opposing requirements. Long carrier lifetime is required in solar cells, CCDs, and most bipolar devices; in high-speed power electronics, controlled deep centers such as Au or Pt are intentionally introduced to shorten switching time. Therefore, it is scientifically insufficient to classify a metal impurity as absolutely “harmful” or “beneficial”: the criterion must be linked to device function, doping type, injection level, and the microscopic state of the impurity. [5,8,18]

The aim of this article is to compare the effects of various metal impurities on recombination in silicon within a unified SRH framework, to distinguish dissolved point centers from precipitates and extended defects, and to develop evidence-based conclusions for technological control. As an analytical contribution, the relationships among the metal group in the periodic table, lattice position, capture-cross-section asymmetry, and material type are summarized within a single causal scheme.

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

2 MATERIALS AND METHODS

The study was carried out as a systematic analytical review. Sources were checked against official OAK requirements, publisher pages, repositories of scientific organizations, and DOI records. The selection included foundational works on SRH theory, articles measuring energy levels and capture cross sections of metal impurities, studies determining metal content in multicrystalline silicon by instrumental neutron activation analysis, Russian-language EBIC studies, and Ni-cluster gettering experiments by researchers from Uzbekistan. The time interval covered 1952-2025; textbooks and secondary web sources were not used as primary evidence. In accordance with the technical requirements published by OAK in 2026, the abstract was organized according to IMRAD logic, metadata were provided in several languages, and references included DOIs. [1]

For each metal, the predominant lattice state, donor or acceptor character, energy level relative to the valence or conduction band, electron and hole capture cross sections, the material type most sensitive under low injection, and the tendency to precipitate were extracted. Because direct comparison of absolute lifetimes obtained by different methods is limited, the main analytical criterion was the capture-cross-section ratio $k = \sigma_n/\sigma_p$ together with qualitative predictions of the SRH model. Results on Fe-B pairing and measurements by QSSPC, microwave photoconductance decay, DLTS, EBIC, and photoluminescence were interpreted together with their experimental conditions. [5-7,12,14-17]

$$U_{SRH} = \frac{np - n_i^2}{\tau_{p0}(n + n_1) + \tau_{n0}(p + p_1)}$$

$$\tau_{n0} = \frac{1}{\sigma_n v_{th} N_t}; \quad \tau_{p0} = \frac{1}{\sigma_p v_{th} N_t}$$

$$\frac{1}{\tau_{eff}} = \frac{1}{\tau_{SRH}} + \frac{1}{\tau_{Auger}} + \frac{1}{\tau_{rad}} + \frac{1}{\tau_{surf}}$$

$$L = \sqrt{D\tau_{eff}}$$

(1)-(2) SRH rate, intrinsic recombination channels, and diffusion length

Here, N_t is the concentration of active centers, σ_n and σ_p are the electron and hole capture cross sections, v_{th} is the thermal velocity, n and p are the carrier concentrations, and n_1 and p_1 are equilibrium quantities related to the defect-level energy. The equations show that recombination becomes stronger as the center energy approaches the middle of the band gap and as the capture cross sections increase. However, when σ_n and σ_p differ strongly, the detrimental effect is distributed differently between p- and n-type material and also depends on the injection level.

3 RESULTS

3.1 SRH Parameters of Point Metal Centers

The comparison results are given in Table 1. For Fe_i, σ_n/σ_p is approximately 700; for V_i, it is 1.7×10^4. In low-injection p-type silicon, electrons are minority carriers, so donor centers that rapidly capture them sharply reduce the lifetime. In n-type silicon, the slower hole-capture process limits the rate for these same centers. For Au_s and Zn_s acceptor centers, the ratio is below unity and the trend is

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

reversed. The k value for Cr_i is close to 2, so its p/n-type asymmetry is much smaller than that of Fe or V. [5]

Table 1. Recombination parameters of selected point metal centers in silicon at 300 K

Center	Lattice site	Level type	Energy	σ_n, cm²	σ_p, cm²	k
Ti_i I	interstitial	donor	E_c -0.27 eV	3.1×10^{-14}	1.4×10^{-15}	22
Ti_i II	interstitial	double donor	E_v+0.26 eV	1.3×10^{-14}	2.8×10^{-17}	460
V_i	interstitial	double donor	E_v+0.36 eV	5×10^{-14}	3.0×10^{-18}	17000
Cr_i	interstitial	donor	E_c -0.22 eV	2.3×10^{-13}	1.1×10^{-13}	2
Mo_i	interstitial	donor	E_v+0.28 eV	1.6×10^{-14}	6.0×10^{-16}	30
Fe_i	interstitial	donor	E_v+0.38 eV	5×10^{-14}	7×10^{-17}	700
Au_s	substitutional	acceptor	E_c -0.55 eV	1.4×10^{-16}	7.6×10^{-15}	0.02
Zn_s	substitutional	acceptor	E_v+0.33 eV	1.5×10^{-15}	4.4×10^{-15}	0.34

Note: i - interstitial, s - substitutional; $k = \sigma_n/\sigma_p$. Values are based on the table of Macdonald and Geerligs [5], taking experimental uncertainties into account.

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

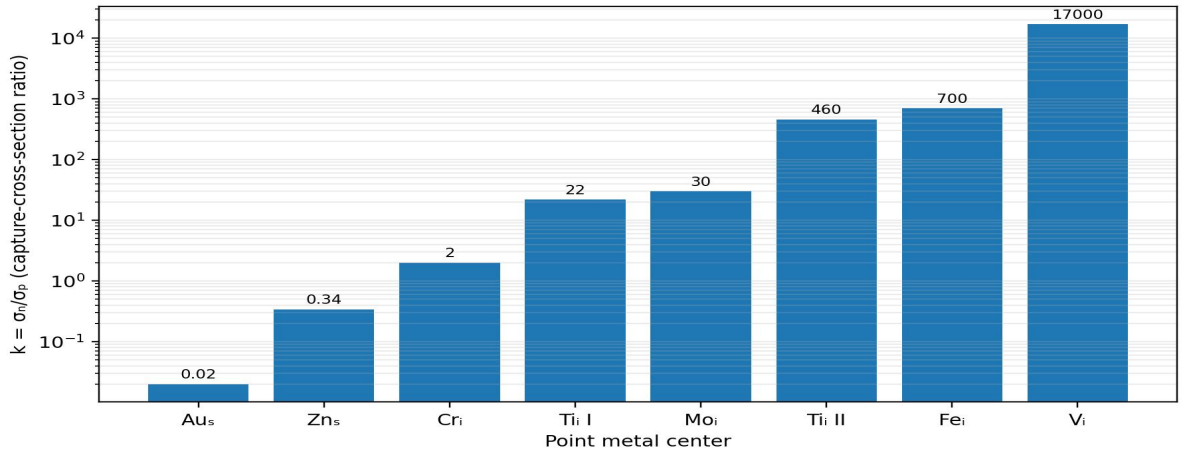


Figure 1. Asymmetry of electron and hole capture cross sections (author visualization based on data from [5])

3.2 Pairing of Iron and Chromium with Dopants

In p-type boron-doped silicon, positively charged Fe_i and negatively charged B_s attract each other and form an FeB pair. The deep donor level of Fe_i at E_v+0.38 eV and the strong asymmetry between its electron and hole capture cross sections cause strong recombination under low injection. At low injection, the FeB pair is generally less active than Fe_i, although their relative activities may change at high injection. Consequently, lifetime measurements before and after dissociation of FeB by illumination or heat have become an industrial method for determining Fe_i concentration. Transient dissociation after a 10 min treatment at 210 °C has been shown to enable mapping of Fe at levels of 10^9-10^{10} cm^{-3}. [6,12,14]

Cr also forms a CrB pair with boron, but the asymmetry of its point-center parameters is smaller than that of Fe. Because metal-dopant pairs are metastable, $\tau_e$ff measured at a single injection level does not fully characterize the material state. Failure to report illumination history, the time before measurement, and the temperature protocol leads to systematic errors when Fe or Cr concentration is back-calculated from lifetime data.

3.3 Copper, Nickel, Cobalt, and Extended Defects

Cu, Ni, and Co diffuse very rapidly in silicon. During cooling, their interstitial concentration decreases quickly, and the atoms precipitate as silicides and multimetal phases at surfaces, grain boundaries, dislocations, or pre-existing microdefects. Therefore, in p-type silicon the measurable recombination activity of isolated Cu, Ni, and Co centers may be lower than that of Fe, but activity increases sharply when precipitates form or dislocations become decorated. In such regions, a dense band of capture levels acts together with the potential field around charged precipitates. [7,13]

In Russian-language EBIC studies, Cu introduced at high temperature increased the recombination contrast of dislocation traces in p-type monocrystalline silicon; Ni introduced during room-temperature chemical-mechanical treatment increased the activity of dislocations and their traces, whereas Cu produced no significant change under the same conditions. Thus, apparently

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

contradictory results for the same metal can be explained by differences in diffusion temperature, precipitation nuclei, and defect geometry. [15,16]

Researchers from Uzbekistan showed that controlled diffusion of Ni at 800-850 °C can produce near-surface Ni clusters that act as gettering centers for uncontrolled recombination-active impurities such as Cu, Fe, and Cr. In some samples, the lifetime of nonequilibrium carriers in the base increased by up to a factor of two. This does not mean that Ni itself is always beneficial: the benefit depends on cluster location and on the removal of other metals from the active volume; uncontrolled Ni may instead create additional recombination in the emitter or at extended defects. [17]

3.4 Metal Concentration and Device Response

In classic controlled-doping experiments, Ti at concentrations above 10^{11} cm^{-3} significantly degraded solar-cell parameters; 2×10^{14} cm^{-3} Ti reduced carrier lifetime by more than one order of magnitude and lowered cell efficiency by 63%. For Fe, degradation began at approximately 2×10^{14} cm^{-3}, and at 1.7×10^{15} cm^{-3} the efficiency decreased by 46%. Cu up to 10^{16} cm^{-3} had a relatively weak effect on the p-type cells in that experiment, while at higher concentrations losses associated with excess p-n junction current and precipitates were observed. These values refer to a specific 1980 cell architecture and thermal process and should not be transferred directly as limits for modern high-efficiency devices. [9,10]

In modern multicrystalline-material experiments, approximately the same 2% relative efficiency loss corresponded to adding 0.1 ppm by mass Ti, 8 ppm Cr, 11 ppm Fe, 13 ppm Ni, or 8 ppm Cu to the melt. This ranking confirms that Ti is a very strong point recombination center, but the active fraction in the final wafer changes substantially through segregation, precipitation, and gettering. Therefore, the raw-material concentration, total wafer concentration, and electrically active center density must be measured as three distinct quantities. [12]

4 DISCUSSION

The results support dividing metal impurities into four groups. The first group consists of dissolved interstitial donors such as Fe_i, V_i, Ti_i, and Mo_i; they have large k values and are particularly detrimental in low-injection p-type bases. The second group consists of substitutional acceptors such as Au_s and Zn_s; they efficiently capture minority holes in n-type silicon. The third group comprises metastable pairs such as FeB and CrB, whose activity depends on illumination and thermal history. The fourth group includes Cu_xSi_y, $NiSi_2$, $FeSi_2$, and multimetal precipitates, as well as metal-decorated grain boundaries; in these cases, surface area, size, charge, and extended-defect density are decisive. [5-8,11-13]

The general statement that p-type material is always more vulnerable to metals is incomplete. It is valid under low-injection conditions when interstitial donor centers dominate. If substitutional acceptors such as Au or Cu and Ni precipitates dominate, n-type material can also degrade strongly. In addition, because the electron diffusion coefficient is higher than the hole diffusion coefficient, a longer lifetime is required in an n-type base to achieve the same diffusion length. Therefore, device quality cannot be assessed solely from τ; $L = \sqrt{(D\tau_{eff})}$ and the device operating injection level must also be considered. [5]

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

The gettering strategy must also match metal-specific kinetics. Phosphorus diffusion is effective at removing Fe and many rapidly diffusing metals from the active volume; in a 2025 industrial n-type SHJ experiment, optimized PDG reduced Fe and increased average efficiency by 0.21 percentage points, although the process also introduced residual O, P, and Cu. Short gettering is insufficient for slowly diffusing Ti and Mo; when precipitates are present, the overall rate may be limited by their dissolution. Hydrogenation can passivate some centers but is not a universal solution for all metals and precipitate types. [13]

A practical diagnostic sequence may be organized as follows: limit surface recombination through high-quality passivation; measure $\tau_e$ff as a function of injection using QSSPC or photoluminescence; separate Fe_i through FeB dissociation; investigate deep levels by DLTS; identify local precipitate and dislocation regions by EBIC or PL imaging; and, when necessary, measure total concentration by NAA, ICP-MS, or SIMS. Only this multimethod approach can distinguish the electrically active fraction from the total metal content. A single room-temperature τ measurement cannot reliably identify the metal species.

A limitation of this review is that capture cross sections reported in different sources are sensitive to temperature, electric field, and measurement method; moreover, the base thickness and passivation of historical solar cells differ from those of current PERC, TOPCon, or SHJ structures. Therefore, the tabulated parameters were used to compare mechanisms, whereas older degradation thresholds were used only to indicate orders of magnitude. Establishing an exact technological limit requires experimental recalibration of SRH parameters for the specific wafer under consideration.

5 CONCLUSION

1. The recombination effect of a metal impurity cannot be evaluated from the element name or total concentration alone; the active state, lattice site, precipitate morphology, and interaction with extended defects must be determined together.
2. Interstitial donors such as Fe_i, V_i, Ti_i, and Mo_i are strong SRH centers in low-injection p-type silicon because of their large electron-capture cross sections. Substitutional acceptors such as Au_s pose a greater risk in n-type material.
3. FeB and CrB pairs are metastable and cause lifetime to depend on illumination and temperature history; injection-dependent measurements before and after pair dissociation are required for Fe determination.
4. The principal risk from Cu, Ni, and Co often appears through precipitates, p-n junction shunts, or metal-decorated dislocations. Controlled Ni clusters can collect other harmful metals from the active volume and serve as gettering centers.
5. The technological solution must be metal-specific: limiting the contamination source, controlling the cooling profile, phosphorus-diffusion gettering, targeted cluster getters, and hydrogen passivation provide reliable results only when verified by multimethod diagnostics.

STATEMENTS ON PUBLICATION ETHICS

Conflict of interest. To be completed by the author before submission of the article.

Funding. To be specified by the author before submission of the article.

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

Data availability. The numerical values and conclusions in the article are based on open bibliographic sources; no new experimental data were generated.

Use of artificial intelligence. Generative artificial intelligence was used in drafting the article and for language editing. The bibliography and technical conclusions should be verified against the primary sources, and scientific responsibility for the final text must be accepted by the named author.

REFERENCES

1. Higher Attestation Commission under the Academy of Sciences of the Republic of Uzbekistan. General technical requirements for the content and quality of scientific articles published in scientific journals. 2026. https://oak.uz/userfiles/files/Ilmiy_etiket_va_umumiy_texnik_talablar.pdf
2. Shockley W, Read WT. Statistics of the recombinations of holes and electrons. Physical Review. 1952;87(5):835-842. https://doi.org/10.1103/PhysRev.87.835
3. Hall RN. Electron-hole recombination in germanium. Physical Review. 1952;87(2):387. https://doi.org/10.1103/PhysRev.87.387
4. Richter A, Glunz SW, Werner F, Schmidt J, Cuevas A. Improved quantitative description of Auger recombination in crystalline silicon. Physical Review B. 2012;86:165202. https://doi.org/10.1103/PhysRevB.86.165202
5. Macdonald D, Geerligs LJ. Recombination activity of interstitial iron and other transition metal point defects in p- and n-type crystalline silicon. Applied Physics Letters. 2004;85(18):4061-4063. https://doi.org/10.1063/1.1812833
6. Istratov AA, Hieslmair H, Weber ER. Iron and its complexes in silicon. Applied Physics A. 1999;69:13-44. https://doi.org/10.1007/s003390050968
7. Istratov AA, Weber ER. Electrical properties and recombination activity of copper, nickel and cobalt in silicon. Applied Physics A. 1998;66:123-136. https://doi.org/10.1007/s003390050649
8. Graff K. Metal Impurities in Silicon-Device Fabrication. 2nd ed. Berlin: Springer; 2000. https://doi.org/10.1007/978-3-642-57121-3
9. Davis JR, Rohatgi A, Hopkins RH, Blais PD, Rai-Choudhury P, McCormick JR, Mollenkopf HC. Impurities in silicon solar cells. IEEE Transactions on Electron Devices. 1980;27(4):677-687. https://doi.org/10.1109/T-ED.1980.19922
10. Rohatgi A, Davis JR, Hopkins RH, et al. Effect of titanium, copper and iron on silicon solar cells. Solid-State Electronics. 1980;23(5):415-422. https://doi.org/10.1016/0038-1101(80)90076-3
11. Istratov AA, Buonassisi T, McDonald RJ, et al. Metal content of multicrystalline silicon for solar cells and its impact on minority carrier diffusion length. Journal of Applied Physics. 2003;94(10):6552-6559. https://doi.org/10.1063/1.1618912
12. Peaker AR, Markevich VP, Coutinho J. Recombination via point defects and their complexes in solar silicon. Physica Status Solidi A. 2012;209(10):1984-1993. https://doi.org/10.1002/pssa.201200216
13. Liu A, Phang SP, Macdonald D. Gettering in silicon photovoltaics: a review. Solar Energy Materials and Solar Cells. 2022;234:111447. https://doi.org/10.1016/j.solmat.2021.111447

HSR (LONDON),
HOUGHTON STREET REVIEW JOURNAL
ISSN: 2058-5519|Impact factor-15.9
http://houghtonstreetreview.com/index.php/hsr

14. Palais O, Yakimov E, Martinuzzi S. Minority carrier lifetime scan maps applied to iron concentration mapping in silicon wafers. Materials Science and Engineering B. 2002;91-92:216-219. https://doi.org/10.1016/S0921-5107(01)00998-9
15. Feklisova OV, Yakimov EB. Vliyanie medi na rekombinatsionnuyu aktivnost protyazhennykh defektov v kremnii [Effect of copper on recombination activity of extended defects in silicon]. Fizika i Tekhnika Poluprovodnikov. 2015;49(6):732-736. (In Russ.). https://doi.org/10.1134/S106378261506010X
16. Orlov VI, Yarykin NA, Yakimov EB. Vliyanie nikelya i medi, vvedennykh pri komnatnoi temperature, na rekombinatsionnye svoistva protyazhennykh defektov v kremnii [Effect of nickel and copper introduced at room temperature on extended defects in silicon]. Fizika i Tekhnika Poluprovodnikov. 2019;53(4):433-436. (In Russ.). https://doi.org/10.21883/FTP.2019.04.47672.9020
17. Bakhadyrkhanov MK, Kenzhaev ZT, Koveshnikov SV, Ayupov KS, Kosbergenov EZh. Vliyanie nikelya na vremya zhizni nositelei zaryada v kremnievykh solnechnykh elementakh [Effect of nickel on carrier lifetime in silicon solar cells]. Fizika i Tekhnika Poluprovodnikov. 2022;56(1):128-133. (In Russ.). https://doi.org/10.21883/FTP.2022.01.51823.9642
18. Bemski G. Recombination properties of gold in silicon. Physical Review. 1958;111(6):1515-1518. https://doi.org/10.1103/PhysRev.111.1515
19. Kranert C, et al. Metal contamination of silicon from the furnace atmosphere after crystallization. Journal of Crystal Growth. 2021;559:126026. https://doi.org/10.1016/j.jcrysgro.2021.126026
20. Lindroos J, Savin H. Review of light-induced degradation in crystalline silicon solar cells. Solar Energy Materials and Solar Cells. 2016;147:115-126. https://doi.org/10.1016/j.solmat.2015.11.047
21. Morimasa M. Influence of metal impurities on lifetime. In: Semiconductor Silicon 1998. ASTM Special Technical Publication. 1998:294-304. https://doi.org/10.1520/STP15713S
22. Zhao S, Smith AL, Ahn SH, et al. Iron in p-type silicon: a comprehensive model. Materials Science Forum. 1997;258-263:985-990.