Semiconductor Physics, Quantum Electronics & Optoelectronics, 2026. V. 29, No 3. P. 311-316.

Semiconductor physics

Effect of inter-impurity interaction on concentration of electroactive manganese impurity atoms in silicon

N.F. Zikrillaev[1], K.A. Ismailov[2], S.B. Isamov[1], B.K. Ismaylov[1,2*], Kh.F. Zikrillaev[1], U.Kh. Sodikov[1], M.M. Shoabdurakhimova[1]

[1]*Tashkent State Technical University named Islam Karimov, 2 Universitetskaya Street, 100095 Tashkent, Uzbekistan*
[2]*Karakalpak State University named after Berdakh, 1 Ch. Abdirov Street, 230112 KAR, Nukus, Uzbekistan*
[*]*Corresponding author e-mail: ismaylovb81@gmail.com; i.bayram@karsu.uz*

Abstract. Influence of the concentration of electroactive manganese impurity on interatomic interactions in single-crystalline *p*-type silicon initially doped with boron was investigated. The electrophysical parameters of silicon samples subjected to diffusion doping at a given manganese vapor pressure and subsequent thermal annealing were studied. It was found that almost all of the manganese atoms incorporated in KDB-1 grade *p*-type silicon with boron concentration $N_B \geq 2\cdot10^{16}$ cm^{-3} become electroactive. For theoretical calculations, the concentration value was set equal to the solubility limit of manganese atoms in silicon. At the same time, the concentration of the electroactive manganese atoms in the *n*-type silicon with phosphorus concentration $N_P \approx 10^{16}$ cm^{-3} did not exceed $3\cdot10^{14}$ cm^{-3}. It was shown that the electroactivity of manganese impurity atoms is defined not only by thermodynamic parameters of diffusion but also by the type and concentration of the initial donor or acceptor impurity. It was established that boron atoms can act as nucleation centers for manganese nanoclusters, and these nanoclusters significantly affect the electrical properties of the original silicon. The developed two-stage low-temperature diffusion technology suppresses silicide formation and ensures uniform distribution of electroactive manganese atoms at maximum concentration. The obtained results are of interest for creating nanostructured silicon with tailored electrical, photovoltaic, optical, and magnetic properties, promising for use in electronics.

Keywords: silicon, manganese, boron, phosphorus, inter-impurity interaction, diffusion, concentration of electroactive impurity, nanoclusters.

https://doi.org/10.15407/spqeo29.03.311
PACS 36.40.-c, 61.72.Yx

Manuscript received 21.07.25; revised version received 11.07.26; accepted for publication 16.09.26; published online 25.09.26.

1. Introduction

Diffusion doping of silicon with impurities, particularly manganese, is of interest for creating new functional devices with controlled electrophysical, photoelectric, optical, and magnetic properties. However, obtaining silicon with the highest possible concentration of electroactive manganese atoms remains a challenge. Analysis of the literature has shown that the total manganese concentration and the concentration of electroactive manganese atoms in silicon may differ due to formation of complexes, clusters, and silicides, as well as due to interactions of manganese atoms with the atoms already present in the silicon crystal lattice, particularly boron or phosphorus [1, 2].

Silicon doped with manganese was produced in quartz ampoules with controlled diffusant vapor pressure. The charge carrier concentration was measured using the Hall effect method. It was demonstrated for the first time that when the boron impurity concentration in the initial *p*-type silicon is $N_B \geq 2\cdot10^{16}$ cm^{-3}, practically all of the introduced manganese impurity atoms become electroactive. On the other hand, in *n*-type silicon initially doped with phosphorus, the portion of the electroactive manganese impurity atoms amounted to a few percent of the manganese maximum solubility [3–5].

Therefore, further research must account for how the background dopant concentration (such as boron and phosphorus) in the starting material, alongside the thermodynamic processing conditions, affects the final concentration of electroactive impurities in silicon [6–13].

Here, we investigate how the concentration of shallow-level boron dopant in the initial silicon influences the concentration of electroactive manganese impurity, which acts as deep-level centers.

2. Technology and experimental results

The study utilized KDB-grade single-crystal silicon with *p*-type conductivity and resistivities ρ = 1, 4.5, 10, 100, and 220 Ohm·cm, as well as KEF-grade silicon with *n*-type conductivity and resistivities ρ = 2, 10, 25, 70, and 200 Ohm·cm. The residual oxygen concentration was $N_{O_i} \approx (5...7)\cdot 10^{17}\,\text{cm}^{-3}$. All the silicon samples, measuring 8×4×1 mm^3, were cut from an ingot using an STX-402 diamond wire cutting machine. After cutting, the samples were chemically etched in a solution HNO_3:HF (3:1), cleaned by boiling in a peroxide-ammonia solution NH_4OH:H_2O_2:H_2O (1:4:12), and further cleaned in a 10% HF solution.

Manganese impurity was incorporated by diffusion from gas phase under identical conditions for all the silicon samples at a temperature *T* = 1160 °C and a diffusion time up to *t* = 1 hour. Two samples of each of the *p*- and *n*-conductivity types were placed separately in each quartz ampoule.

Simultaneously, control samples containing no manganese impurity were thermally annealed under the same conditions to assess the effect of the diffusion temperature on the electrical properties of manganese-doped silicon samples.

During diffusion in quartz ampoules, the manganese vapor pressure did not exceed $P = 10^{-6}$ mmHg. The diffusion coefficient of the manganese atoms in silicon was determined by the following relationship [14]:

$$D = 0.26 \cdot \exp\left(\frac{E_a}{kT}\right), \frac{\text{cm}^2}{s}, \quad (1)$$

where *k* is the Boltzmann constant ($k = 1.38\cdot 10^{-23}$ J/K), and E_a is the diffusion activation energy (E_a = 1.3 eV), respectively.

The solubility of manganese in silicon was determined by the following expression:

$$N_{\text{Mn}} = 2.5\cdot 10^{22} \cdot \exp\left(\frac{-2.1}{kT}\right), \text{cm}^{-3}, \quad (2)$$

According to the results of [15], the total solubility of manganese in silicon at a temperature *T* = 1090 °C is $N_{\text{Mn}} \sim 10^{16}$ cm^{-3}.

Diffusion of manganese atoms into silicon was carried out in a MAGNETIC electric furnace, providing temperature control with an accuracy of ± 0.5 °C.

Initially, the samples were heated from room temperature (30 °C) to 580…680 °C at 5 °C/min and held for 10…20 min. The temperature was then ramped at 15…20 °C/min up to the high value corresponding to diffusion regime (980…1250 °C) and maintained for 20…40 min (Fig. 1). Finally, the quartz ampoules were extracted from the furnace and quenched in technical oil at a cooling rate of ~150…200 °C/s.

In the remainder of the text, the stated diffusion temperature corresponds to the peak final temperature of the process. The specific thermal history and this final temperature govern the proportion of electrically active manganese atoms.

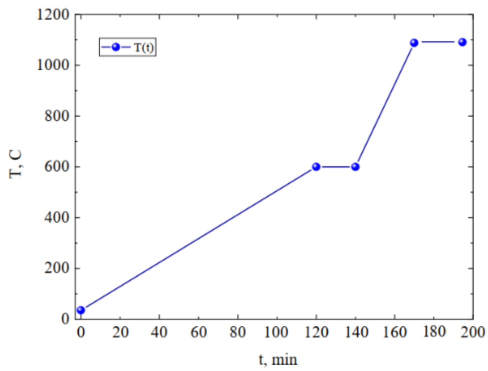

Fig. 1. Temperature regimes of diffusion of manganese impurity into silicon.

Then the samples were mechanically ground with M-14 silicon carbide abrasive (removing a ~ 50 μm thick layer on all sides) to remove manganese silicides and chemically etched in an HF:HNO_3 (1:8) solution for *t* = 3 min to remove the Si surface layer with grinding-induced defects. The described procedure enabled formation of *p*-type samples with the resistivity ρ = 10^3…10^5 Ohm·cm.

3. Experimental methodology

Measurements of electrophysical characteristics of silicon samples after diffusion of manganese impurity were performed using an Ecopia Hall HMS-7000 van der Pauw setup. The results showed that, regardless of ide-tical diffusion conditions (temperature, diffusion time, cooling rate), the concentration of electroactive manganese atoms significantly depended on the concentration of boron or phosphorus impurity in the original silicon.

The total concentration of electroactive manganese atoms was determined by solving the electroneutrality equation based on the obtained experimental results, taking into account the degree of filling of both energy levels of the manganese atoms ($E_1 = E_c - 0.24$ eV, $E_2 = E_c - 0.5$ eV) in the silicon band gap.

For the compensated *p*-type silicon samples (*p*-Si⟨B,Mn⟩), the concentration of manganese atoms was determined by solving the following neutrality equation:

$$N_{\text{Mn}} = \frac{1}{2}\left(p_0 - p - N_{TD}\right). \quad (3)$$

For overcompensated silicon samples (*n*-Si⟨B,Mn⟩), the concentration of manganese atoms was determined as the solution of the following equation:

$$N_{\text{Mn}} = p_0 + n_0 + f(E_1)N_{\text{Mn}} + f(E_2)N_{\text{Mn}} - N_{TD}. \quad (4)$$

The concentration of manganese atoms in *n*-Si⟨P,Mn⟩ was determined from the following equations:

$$N_{\text{Mn}} = \frac{1}{2}\left(n - n_0 + f(E_1)N_{\text{Mn}} + f(E_2)N_{\text{Mn}} - N_{TD}\right). \quad (5)$$

$$n_0 = \sqrt{N_C N_D}\exp\left(-\frac{E_C - E_D}{2kT}\right), \quad (6)$$

$$p_0 = \sqrt{N_C N_A} \exp\left(-\frac{E_A - E_V}{2kT}\right), \quad (7)$$

$$E_F = \frac{E_C + E_D}{2} + \frac{kT}{2} \ln \frac{N_D}{N_C}, \quad (8)$$

where p_0 and p are the hole concentrations before and after diffusion of manganese, n_0 and n are the electron concentrations before and after the diffusion, N_{TD} is the thermal donor concentration, $f(E_1)$ and $f(E_2)$ are the filling degrees of the 1st and 2nd energy levels of manganese atoms, E_D and E_A are the activation energies of boron and phosphorus atom levels, and E_F is the Fermi level, respectively. The hole concentrations p_0 and p as well as the concentrations of electrons n_0 and n were determined from Hall measurements of electrical parameters of silicon samples before and after the diffusion. The N_{TD} concentration was determined by measuring the charge carrier concentration before and after thermal annealing in control (undoped, annealed under the same conditions) silicon samples.

Fig. 2 shows concentrations of electroactive manganese impurity atoms in silicon. As can be seen from this figure, the concentration of the electroactive manganese atoms in the samples with the resistivity ρ = 1 Ohm·cm is almost two orders of magnitude higher than in the samples with the resistivity ρ = 220 Ohm·cm despite the fact that these samples were doped in the same ampoule under absolutely identical process conditions.

The concentration of the electroactive manganese impurity atoms in the initial silicon with the resistivity ρ = 1 Ohm·cm reaches N_{Mn} = 1.2·10^{16} cm^{-3}, which is practically close to the manganese maximum solubility at 1200 °C (N_{Mn} = 2·10^{16} cm^{-3}). Under the same diffusion conditions, the manganese concentration in the initial silicon with a resistivity ρ = 220 Ohm·cm does not exceed (3…3.5)·10^{14} cm^{-3}, *i.e.*, almost two orders of magnitude less than in the KDB-1 silicon samples. It was found therefore that the concentration of the electroactive manganese impurity atoms depends on the boron concentration in the initial silicon.

It is known that the concentration of boron impurity atoms in KDB-1 silicon is N_B = 2·10^{16} cm^{-3}, while for samples with the resistivity ρ = 220 Ohm·cm (KDB-220), it is N_B = 1.5·10^{13} cm^{-3}, which corresponds to the observed difference in the concentrations of the electroactive manganese impurity in both cases. These results demonstrate that under identical doping process conditions, the electroactive manganese concentration is defined by the boron concentration in the original silicon.

The resistivity of the KDB-1 silicon samples reaches ρ ≈ 3.4·10^4 Ohm·cm after diffusion of manganese at a temperature T = 1200 °C. At the same time, the samples with the initial resistivity ρ = 100 Ohm·cm, the boron concentration in which is N_B = 2·10^{14} cm^{-3}, become n-type with the resistivity ρ ≈ 5.8·10^2 Ohm·cm after diffusion of manganese at the same temperature as in the previous cases.

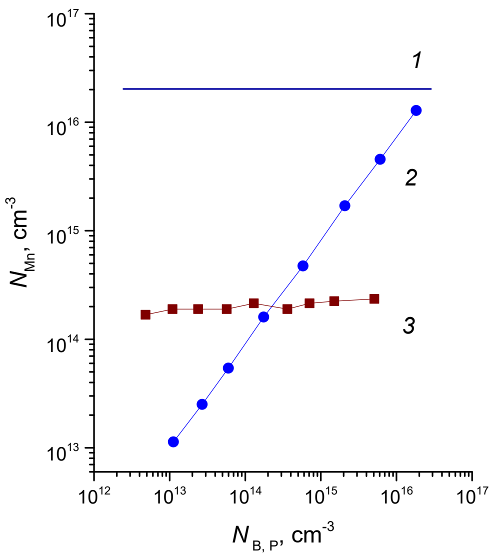

Fig. 2. Concentrations of electroactive manganese atoms *versus* concentration of boron or phosphorus in the original silicon. *1* – maximum solubility of manganese in silicon (1160 °C); *2* – dependence of the concentration of electroactive manganese atoms on the boron concentration in the original silicon; *3* – dependence of the concentration of electroactive manganese atoms on the phosphorus concentration in the original silicon.

It was found therefore that the concentration of the electroactive manganese atoms increases at increasing the boron concentration in the original silicon. At N_B ~ 2·10^{16} cm^{-3}, almost all of the embedded manganese atoms become electroactive [16–20]. Unlike this, in the KDB-100 case, the concentration of the electroactive manganese impurity reaches only about 1% of the total dissolved manganese concentration.

The effect of the phosphorus concentration in the initial n-type (KEF) silicon on the concentration of electroactive manganese impurity was also studied. The obtained results showed that, unlike the cases of initial silicon with boron impurity (p-type conductivity), this concentration is independent of the phosphorus concentration in the initial material.

The concentration of the electroactive manganese impurity atoms obtained at the studied diffusion temperatures T = 1000…1270 °C is approximately N_{Mn} = (2…2.5)·10^{14} cm^{-3}, which is almost two orders of magnitude lower than the concentration of the manganese impurity atoms in the initial KDB-1 silicon (curve *3*). These results demonstrate that the concentration of the electroactive manganese atoms significantly depends on the conductivity type and the concentration of boron and phosphorus in the initial silicon.

As can be seen from Table 1, depending on the initial concentration of boron impurity, materials with different electrophysical parameters (specific resistance and conductivity type) can be obtained at the same temperature and time of diffusion annealing.

Table 1. Resistivity of silicon samples doped with manganese impurity as a function of the initial boron concentration at various diffusion temperatures. The diffusion time at all the temperatures is t = 60 min.

Diffusion temperature, °C	KDB-1 $2\cdot10^{16}$ cm^{-3}	KDB-2 10^{16} cm^{-3}	KDB-4.5 $6\cdot10^{15}$ cm^{-3}	KDB-10 $2\cdot10^{15}$ cm^{-3}	KDB-100 $2\cdot10^{14}$ cm^{-3}
1050	65* *p*-type	$1\cdot10^{2}$ *p*-type	$3\cdot10^{2}$ *p*-type	$2\cdot10^{5}$ *p*-type	$1.6\cdot10^{3}$ *n*-type
1100	80 *p*-type	$6\cdot10^{3}$ *p*-type	$1.6\cdot10^{5}$ *p*-type	$9.2\cdot10^{3}$ *n*-type	$4\cdot10^{2}$ *n*-type
1150	$1.2\cdot10^{3}$ *p*-type	$8\cdot10^{4}$ *n*-type	$2.3\cdot10^{4}$ *n*-type	$1.4\cdot10^{2}$ *n*-type	60 *n*-type
1200	$6.4\cdot10^{4}$ *p*-type	$1.5\cdot10^{4}$ *n*-type	$7.5\cdot10^{3}$ *n*-type	$8.5\cdot10^{2}$ *n*-type	34 *n*-type

*Specific electrical resistivity of the samples after doping

4. Discussion

Electron paramagnetic resonance (EPR) studies of silicon samples doped with manganese impurity revealed [21, 22] that manganese atoms form nanoclusters, each consisting of four atoms located in nearby interstitial positions of the silicon crystal lattice. Broadening of the EPR spectrum to 21 lines [21] confirms close relative positions of these nanoclusters, caused by resonant interaction of the manganese atom d-shells containing unpaired electrons.

It has been found out that manganese atoms cannot form nanoclusters without additional thermal annealing. X-ray diffraction analysis [23] revealed that manganese nanoclusters contain boron atoms. Presence of Mn_xB_y peaks indicates the possibility of manganese nanoclusters forming around a nodal boron atom [23]. Furthermore, boron atoms serve as nuclei for formation of interstitial manganese nanoclusters. Consequently, the initial concentration of boron atoms in silicon influences the electroactivity by stimulating formation of manganese atom clusters in the lattice.

X-ray dispersive analysis of *n*-type silicon samples doped with manganese impurity showed that nanoclusters do not form in these samples. This confirms that presence of boron impurity atoms in the original silicon is a necessary condition for the formation of manganese nanoclusters.

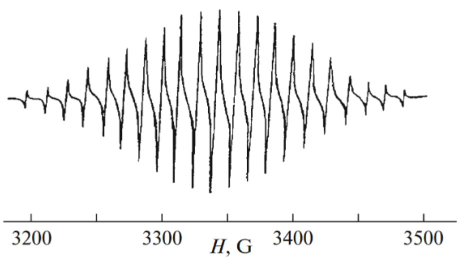

Fig. 3. EPR spectrum of a nanocluster consisting of four manganese atoms in silicon [21].

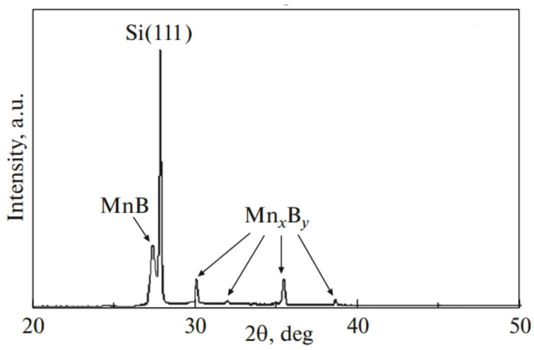

Fig. 4. X-ray dispersion analysis of a silicon sample with manganese nanoclusters [23].

5. Conclusions

Analysis of the obtained results reveal that the electroactive manganese impurity atoms in silicon significantly depends on the type and concentration of donor and acceptor impurities present in the starting material. At a boron concentration $N_B \geq 2\cdot10^{16}$ cm^{-3}, almost complete activation of the manganese atoms is achieved (up to $N_{Mn} \sim 1.2\cdot10^{16}$ cm^{-3}). In *n*-type silicon, the concentration of the electroactive manganese does not exceed $N_{Mn} \approx (2\ldots3)\cdot10^{14}$ cm^{-3} even at high diffusion temperatures. It is shown that use of the developed low-temperature two-stage diffusion technology under controlled vapor pressure of manganese during the diffusion process significantly reduces the concentration of electroactive manganese atoms. Therefore, optimization of diffusion doping parameters including selection of initial silicon based on the concentration of impurity atoms as well as choice of temperature, diffusion time, and vapor pressure of the diffusant are key factors in obtaining silicon with specified electrophysical parameters.

References

1. Khanna V., Singh R., Claes P. *et al.* Evolution of vibrational spectra in the manganese–silicon clusters Mn_2Si_n, n = 10, 12 and 13, and cationic $[Mn_2Si_{13}]^+$. *J. Phys. Chem.* 2022. **126**, No 10. P. 1617–1626. https://doi.org/10.1021/acs.jpca.1c10027.

2. Bolduc M., Awo-Affouda C., Stollenwerk A. *et al*. Above room-temperature ferromagnetism in Mn-ion implanted Si. *Phys. Rev. B*. 2005. **71**. Art. 033302. https://doi.org/10.1103/PhysRevB.71.033302.
3. Ismailov K.A., Iliev X.M., Tursunov M.O., Ismaylov B.K. Formation of complexes consisting of impurity Mn atoms and group VI elements in the crystal lattice of silicon. *SPQEO*. 2021. **24**. P. 255–260. https://doi.org/10.15407/spqeo24.03.255.
4. Zikrillaev N.F., Koveshnikov S.V., Trabzon L. *et al*. Ferromagnetic properties of silicon doped manganese atoms. *Surf. Eng. Appl. Electrochem*. 2025. **61**. P. 75–80. https://doi.org/10.3103/S1068375524700571.
5. Tursunov M.O., Iliev Kh.M., Ismaylov B.K. High-temperature analysis of silicon properties with manganese-oxygen binary complexes. *Phys. Sci. Technol*. 2024. **11**, No 1. P. 4–12. https://doi.org/10.26577/phst2024v11i1a1.
6. Bakhadyrkhanov M.K., Isamov S.B., Zikrillaev N.F., Tursunov M.O. Anomalous photoelectric phenolmena in silicon with nanoclusters of manganese atoms. *Semiconductors*. 2021. **55**, No 6. P. 636–639. https://doi.org/10.1134/s1063782621060038.
7. Gadiyak G.V. Diffusion of boron and phosphorus in silicon during high-temperature ion implantation. *Semiconductors*. 1997. **31**, No 4. P. 385–389. https://doi.org/10.1134/1.1187179.
8. Iliyev X.M., Odzhaev V.B., Isamov S.B. *et al*. X-ray diffraction and Raman spectroscopy analyses of GaSb-enriched Si surface formed by applying diffusion doping technique. *East Eur. J. Phys*. 2023. **38**, No 3. P. 363–369. https://doi.org/10.26565/2312-4334-2023-3-38.
9. Yang W., Li Y., Meng F. *et al*. III–V compound materials and lasers on silicon. *J. Semicond.* **40**. 2019. P. 101305. http://doi.org/10.1088/1674-4926/40/10/101305.
10. Monzur-Ul-Akhir A.M., Mori M., Maezawa K. Heteroepitaxial growth of InGaSb on GaSb/Si(111)–√3×√3-Ga surface phase with a two-step growth method to investigate the impact of high-quality GaSb buffer layer. *phys. status solidi (b)*. 2017. **254**, No 2. P. 1600528. https://doi.org/10.1002/pssb.201600528.
11. Zikrillaev N.F., Koveshnikov S.V., Turekeev X.S., Ismailov B.K. Composition of silicon alloyed with gallium and phosphorus atoms. *J. Surf. Invest.: X-ray, Synchrotron and Neutron Tech*. 2024. **18**, No 1. P. 69–73. https://doi.org/10.1134/S102745102401021X.
12. Bakhadyrhanov M.K., Sodikov U.X., Iliev Kh.M. *et al*. Perspective material for photoenergetics on the basis of silicon with binary elementary cells mater. *Phys. Chem*. 2022. **4**, No 1. P. 1–6. https://doi.org/10.18282/mpc.v1i1.569.
13. Christensen J.S., Radamson H.H., Kuznetsov A.Yu., Svensson B.G. Phosphorus and boron diffusion in silicon under equilibrium conditions. *Appl. Phys. Lett*. 2003. **82**, No 14. P. 2254–2256. https://doi.org/10.1063/1.1566464.
14. Rinkevich A.B., Korolev A.V., Samoylovich M.I. *et al*. Magnetic properties of 3D nanocomposites consisting of an opal matrix with embedded spinel ferrite particles. *Tech. Phys*. 2016. **6**. P. 194–201. https://doi.org/10.1134/S1063784216020183.
15. Tiecheng L., Congxiao L., Chen J. *et al*. Improving room-temperature ferromagnetism in Mn-implanted Si by high-temperature annealing. *IEEE Trans. Magn*. 2015. **51**, No 6. Art. ID 2400204. https://doi.org/10.1109/TMAG.2014.2375852.
16. Lindroos J., Fenning D.P., Backlund D.J. *et al*. Nickel: A very fast diffuser in silicon. *J. Appl. Phys*. 2013. **113**. P. 204906. https://doi.org/10.1063/1.4807799.
17. Kenzhaev Z.T., Iliev Kh.M., Odzhaev V.B. *et al*. The effect of gamma irradiation on the electro-physical parameters of nickel-doped silicon solar cells. *Surface Eng. Appl. Electrochem*. 2024. **60**, No 6. P. 851–856. https://doi.org/10.3103/S1068375524700467.
18. Ismailov K.A., Zikrillaev N.F., Ismaylov B.K. *et al*. Nickel clusters in the silicon lattice. *J. Nano-Electron. Phys*. 2024. **16**, No 5. P. 05022. https://doi.org/10.21272/jnep.16(5).05022.
19. Ismaylov B.K., Zikrillayev N.F., Ismailov K.A., Kenzhaev Z.T. Physical mechanism of gettering of impurity Ni atom clusters in Si lattice. *SPQEO*. 2024. **27**. P. 294–297. https://doi.org/10.15407/spqeo27.03.294.
20. Kenzhaev Z.T., Iliev Kh.M., Ismailov K.A. *et al*. Physical mechanisms of gettering properties of nickel clusters in silicon solar cells. *Phys. Sci. Technol*. 2024. **11**, No 1. P. 13–22. https://doi.org/10.26577/phst2024v11i1a2.
21. Bakhadyrkhanov M.K., Iliev Kh.M., Mavlonov G.Kh. *et al*. Silicon with magnetic nanoclusters of manganese atoms as a new ferromagnetic material. *Tech. Phys*. 2019. **64**, No 3. P. 385–388. https://doi.org/10.1134/S1063784219030046.
22. Bakhadyrkhanov M.K., Mavlonov G.Kh., Isamov S.B. *et al*. Transport properties of silicon doped with manganese via low temperature diffusion. *Inorg. Mater*. 2011. **47**. P. 479–483. https://doi.org/10.1134/S0020168511050062.
23. Yunusov Z.A., Yuldashev Sh.U., Igamberdiev Kh.T. *et al*. Ferromagnetic states of *p*-type silicon doped with Mn. *J. Korean Phys. Soc*. 2014. **64**, No 10. P. 1461–1465. https://doi.org/10.3938/jkps.64.1461.

Authors' contributions

Zikrillaev N.F.: formal analysis, writing – original draft.
Ismailov K.A.: writing – review & editing.
Isamov S.B.: conceptualization, methodology, formal analysis, validation.
Ismaylov B.K.: investigation, resources, data curation.
Zikrillaev Kh.F.: writing – original draft, writing – review & editing.
Sodikov U.Kh.: conceptualization, investigation, writing – review & editing.
Shoabdurakhimova M.M.: investigation, resources, writing – review & editing.

Authors and CV

Zikrillaev Nurullo Fatxulaevich. Doctor of Physical and Mathematical Sciences, Professor of the Tashkent Technical University, Tashkent, Uzbekistan. Author of more than 220 works, among which are 5 patents, 5 monographs, 12 textbooks, and educational manuals. https://orcid.org/0000-0002-6696-5265

Ismailov Kanatbay Abdreymovich. Doctor of Physical and Mathematical Sciences, Professor, Head of the Semiconductor Physics Department of the Karakalpak State University, Nukus, Uzbekistan. Author of more than 335 works, among which are 4 patents, 3 monographs, 15 textbooks and educational-methodological manuals. https://orcid.org/0000-0002-1293-106X

Ismaylov Bayrambay Kanatbaevich. Doctoral student (DSc) at the Faculty of Physics of the Karakalpak State University. Author of more than 30 articles and more than 43 abstracts of international and republican conferences. His research interests include use of nanostructured silicon for applications in efficient solar cells. https://orcid.org/0000-0002-5880-4568

Zikrillaev Khayrulla Fatxulaevich. Candidate of Physical and Mathematical Sciences, Associate Professor, Tashkent State Technical University, Tashkent, Uzbekistan. Author of more than 100 scientific papers including 5 patents, 2 monographs, and 4 textbooks and teaching aids. https://orcid.org/0009-0003-5432-1715

Isamov Sobirjon Boltaevich is an Associate Professor at the Department of Digital Electronic and Microelectronics. He received the B.S. degree from the Samarkand State University and the M.S. and PhD degrees from the Tashkent State Technical University. His research is focused on quantum dots containing semiconductors and structures for electronic and optoelectronic devices.
https://orcid.org/0000-0002-3360-2361

Sodikov Usmonkhuja Khasanovich. Doctoral student (DSc) at the Faculty of Electronics and Automation Engineering of the Tashkent State Technical University. Author of more than 20 scientific publications and more than 45 abstracts of international and republican conferences. His expertise concerns electronics, including power electronics, optoelectronics, solar cell efficiency enhancement, and development of novel nanostructured semiconductor materials.
https://orcid.org/0000-0002-4510-1396

Shaobdurakhimova Manzura Mirzokhid qizi. Assistant at the Faculty of Engineering Electronics and Automation of the Tashkent State Technical University. Author of more than 10 scientific publications and more than 20 abstracts of international and republican conferences. Her research interests include autooscillations of current in silicon and use of nanostructured silicon for applications in efficient solar cells. https://orcid.org/0000-0002-1879-6751

Вплив міждомішкової взаємодії на концентрацію електроактивних атомів домішки марганцю в кремнії

N.F. Zikrillaev, K.A. Ismailov, S.B. Isamov, B.K. Ismaylov, Kh.F. Zikrillaev, U.Kh. Sodikov, M.M. Shoabdurakhimova

Анотація. Досліджено вплив концентрації електроактивної домішки марганцю на міжатомні взаємодії в монокристалічному кремнії *p*-типу, початково легованому бором. Досліджено електрофізичні параметри зразків кремнію, що піддалися дифузійному легуванню при заданому тиску пари марганцю та подальшому термічному відпалу. Було виявлено, що майже всі атоми марганцю, що входять до складу кремнію *p*-типу марки KDB-1 з концентрацією бору $N_B \geq 2\cdot10^{16}$ cm^{-3}, стають електроактивними. Для теоретичних розрахунків значення концентрації було встановлено рівним межі розчинності атомів марганцю в кремнії. Водночас, концентрація електроактивних атомів марганцю в кремнії *n*-типу з концентрацією фосфору $N_P \approx 10^{16}$ cm^{-3} не перевищувала $3\cdot10^{14}$ cm^{-3}. Було показано, що електроактивність атомів домішки марганцю визначається не лише термодинамічними параметрами дифузії, але й типом та концентрацією початкової донорної або акцепторної домішки. Було встановлено, що атоми бору можуть виступати центрами нуклеації для нанокластерів марганцю, і ці нанокластери суттєво впливають на електричні властивості вихідного кремнію. Розроблена двостадійна низькотемпературна дифузійна технологія пригнічує утворення силіцидів та забезпечує рівномірний розподіл електроактивних атомів марганцю при максимальній концентрації. Отримані результати становлять інтерес для створення наноструктурованого кремнію із заданими електричними, фотоелектричними, оптичними та магнітними властивостями, перспективним для використання в електроніці.

Ключові слова: кремній, марганець, бор, фосфор, міждомішкова взаємодія, дифузія, концентрація електроактивної домішки, нанокластери.