FAN VA TA'LIM YANGILIKLARI
ILMIY-METODIK JURNAL
ISSN 3093-8694 ◆ saen.uz
2026-yil
11-son

UDK: 621.315.592:539.1.04

Mirzarayimov Jaxongir Zokirjanovich,
Head of the Department of General Education Subjects at the Namangan Academic Lyceum of the Ministry of Internal Affairs of the Republic of Uzbekistan, Doctor of Philosophy (PhD) in Physical and Mathematical Sciences

Makhmudov Sherzod Ahmadovich,
Senior Researcher at the Laboratory of Solid State Physics, Institute of Nuclear Physics, Academy of Sciences of the Republic of Uzbekistan

EFFECT OF γ-RADIATION ON THE LIFETIME OF CHARGE CARRIERS IN SILICON DOPED WITH COPPER AND IRIDIUM

Abstract. Radiation stabilization of the charge carrier lifetime in p-type silicon doped with copper and iridium impurities by measuring the electro physical and recombination properties by the Hall Effect method and stationary photoconductivity before and after gamma irradiation to fluency ~1018 cm-2 is discussed. It is shown that in p-Si <B,P,Cu> and p-Si <B,P,Ir>, the relative change in the concentration of charge carriers is ~ 2 times slower than in control silicon, which is explained by the representation of the probability of the recombination mechanism as the sum of the probabilities of recombination radiation centres and recombination through a barrier mechanism, mutually compensating each other. It was found that by increasing the concentration of copper and iridium in doped silicon, Kτ decreases; second, the value of Kτ in doped silicon is lower than in control silicon, which is explained by the appearance and increase of micro heterogeneity in conductivity in doped silicon.

Key words: neutron transmutation, lifetime of minority charge carriers, NdS-neutron doped silicon, quasi-chemical reactions, thermal defects, concentration of recombination centres.

MIS VA IRIDIY BILAN LEGIRLANGAN KREMNIYDA ZARYAD TASHUVCHILAR YASHASH VAQTIGA γ-NURLANISHNING TA'SIRI

Annotatsiya. Ushbu maqolada mis va iridiy aralashmalari bilan legirlangan p-tipli kremniyda zaryad tashuvchilarning yashash vaqtini radiatsion barqarorlashtirish masalasi ko'rib chiqilgan. Tadqiqotlar gamma-nurlanishdan oldin va keyin Xoll effekti hamda statsionar fotookazuvchanlik usullari yordamida elektrofizik va rekombinatsion xususiyatlarni o'lchash orqali amalga oshirilgan. Nurlanish fluensiyasi taxminan 10^{18} cm^{-2} ni tashkil etgan. Aniqlanishicha, p-Si ⟨B,P,Cu⟩ va p-Si ⟨B,P,Ir⟩ namunalarida zaryad tashuvchilar konsentratsiyasining nisbiy o'zgarishi nazorat kremniyiga nisbatan taxminan ikki baravar sekin kechadi. Bu holat rekombinatsiya mexanizmi ehtimolining rekombinatsion radiatsion markazlar orqali hamda potensial to'siq mexanizmi orqali sodir bo'ladigan rekombinatsiya ehtimollari yig'indisi sifatida ifodalanishi va ularning o'zaro kompensatsiyalanishi bilan izohlanadi. Shuningdek, legirlangan kremniyda mis va iridiy konsentratsiyasining ortishi bilan Kτ kattaligi kamayishi, legirlangan kremniydagi Kτ qiymati nazorat kremniyiga nisbatan past bo'lishi aniqlangan. Bu hodisa legirlangan kremniyda elektr o'tkazuvchanlikning mikrogeterogenligi paydo bo'lishi va ortishi bilan izohlanadi.

Kalit so'zlar: neytron-transmutatsion legirlash, nomuvozanat zaryad tashuvchilarning yashash vaqti, neytronlar yordamida legirlangan kremniy, kvazi-kimyoviy reaksiyalar, radiatsion nuqsonlar, rekombinatsiya markazlari konsentratsiyasi.

ВЛИЯНИЕ γ-ИЗЛУЧЕНИЯ НА ВРЕМЯ ЖИЗНИ НОСИТЕЛЕЙ ЗАРЯДА В КРЕМНИИ, ЛЕГИРОВАННОМ МЕДЬЮ И ИРИДИЕМ

Аннотация. В статье рассматривается вопрос радиационной стабилизации времени жизни носителей заряда в кремнии p-типа, легированном примесями меди и иридия. Исследования электрофизических и рекомбинационных свойств проводились до и после гамма-облучения с использованием метода эффекта Холла и метода стационарной фотопроводимости. Флюенс облучения составлял приблизительно 10^{18} $см^{-2}$. Показано, что в образцах p-Si ⟨B,P,Cu⟩ и p-Si ⟨B,P,Ir⟩ относительное изменение концентрации носителей заряда происходит примерно в два раза медленнее, чем в контрольном кремнии. Это объясняется представлением вероятности рекомбинационного процесса в виде суммы вероятностей рекомбинации через радиационные центры и через барьерный механизм, которые взаимно компенсируют друг друга. Установлено, что с увеличением концентрации меди и иридия в легированном кремнии величина Kτ уменьшается. Кроме того, значение Kτ в легированном кремнии ниже, чем в контрольном. Данное явление объясняется возникновением и увеличением микро неоднородности электропроводности в легированном кремнии.

Ключевые слова: нейтронно-трансмутационное легирование, время жизни неосновных носителей заряда, кремний, легированный нейтронами, квазихимические реакции, радиационные дефекты, концентрация рекомбинационных центров.

INTRODUCTION

Compensated silicon with impurities that create deep energy levels attracts the interest of researchers by the possibility of fabricating various sensors based on it with both increased thermal and radiation resistance [1–15]. In silicon, the introduction of defects that create deep energy levels (DEEs) is one of the ways to form the necessary complex of electrophysical, recombination, and photoelectric properties of a doped material. Therefore, a number of works are devoted to studying the lifetime of charge carriers in silicon with deep radiation and impurity centers [2–6]. It is shown that the lifetime of charge carriers (τ) in doped samples depends on the concentration of introduced impurities Nм, the presence of dislocations in the initial silicon, and the rate of post-diffusion cooling. However, the influence of γ-radiation on the behavior of the lifetime of charge carriers (τ) in silicon with DEL and pre-irradiated silicon (i.e., with induced radiation defects) has practically not been studied.

The lifetime τ , being one of the important parameters, provides information on the kinetics of the processes of electron-hole transitions, the nature of emerging defects, etc. In this regard, in this work, we study the nature of the change in samples p-Si<B,P,Cu> and p-Si<B,P,Ir> - after γ-radiation.

EXPERIMENTAL TECHNIQUE

To study the effect of γ - radiation on τ in doped and control samples, n - and p - type silicon obtained by the Czochralski method [1-12] with a resistivity of 3÷10 Om·cm and a dislocation density of ~104 cm–2 was used as the starting material, as well as an NdS sample. Silicon was doped with copper in the temperature range of 1050÷1275 ° C, followed by slow (at a speed of ~ 30-50 deg/min) or fast (at a speed of ~200 ~250 deg/min) cooling. Radiation treatment of silicon samples was performed in the field of γ - radiation with an intensity of ~750 P·s-1 in the dose range of 107÷109 P. When irradiated, the temperature did not exceed ~50 oC.

To obtain NdS samples, single crystals of p-type silicon with an initial ρ≈ 1 Om·cm were used [12,18-20]. Neutron irradiation was carried out in the vertical channel of the VVR-SM reactor of the INP AS of Republic of Uzbekistan at a power of 8÷10 MW and a thermal neutron intensity of 8·1013 cm-2·s-1. Annealing of radiation defects was performed in the range of 800 ÷ 1250 ° C in air for 1÷5 hours, followed by slow cooling at a speed of 30 ÷ 50 deg / min.

EXPERIMENT RESULTS AND DISCUSSION

Studies of the effect of γ - quanta 60Co to fluences 2 · 1018 cm-2 on the lifetime of non-basic charge carriers in neutron-transmutation doped silicon have shown that with an increase in the degree of silicon compensation by Cu and Ir impurities in p-type NdS, the value of τ degrades ~ 2 times less than that of non-doped neutron-transmutation p-type silicon [2-15,23,24]. This effect is caused by the interaction of impurity atoms with radiation defects.

Figure 1 shows the dependence of the recombination probability of 1 / τ charge on the dose of γ- radiation in doped and control samples. Also, the dependence of the change in the lifetime of charge carriers on the dose of γ- radiation in the samples p - Si<B, P>, p-Si<B,P,Cu> and p-Si<B,P, Ir> was shown. the value of the coefficient of radiation change in the lifetime of charge carriers (Kτ) was determined from the slope of the curves.

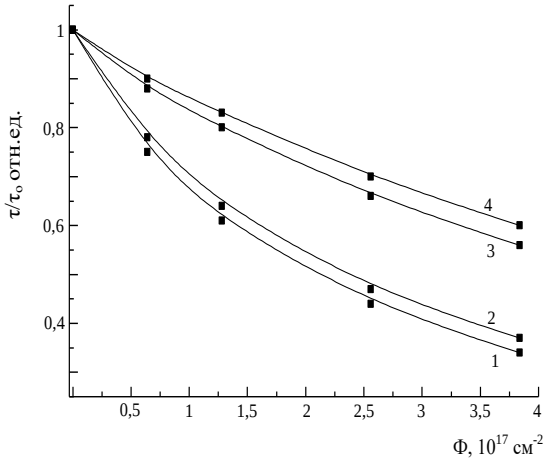


Fig. 1. dependence of τ/τo on the gamma radiation dose in p-Si<B, P> (1,2), p-Si<B,P,Ir>(3) and p-Si<B,P,Cu>(4) samples, TDIF= 1275 C

In the experiment, the value Kτ is determined by the slope of the sections of the dose dependences [Δ(1/τ)] / ΔΦ. At the initial stage of irradiation to a dose of ~4·1017 cm-2, the change in the lifetime of charge carriers in doped and control silicon is satisfactorily described by the following expressions (Fig.2):

$$\tau = \frac{\tau_0}{1 + \tau_0 К_\tau \Phi}$$

where τ, τo, - is the lifetime of charge carriers before and after irradiation, respectively,Φ is the fluence of □ - radiation, and Kτ is the coefficient of radiation change in the lifetime of charge carriers, the values of which are shown in table 1.

As can be seen from the table, firstly, with increasing concentrations of copper and iridium in doped silicon, Kτ decreases; secondly, the value of Kτ in doped silicon is less than in control silicon. These facts are explained as follows. Based on the analysis of the work, we propose a scheme of quasi-chemical reactions occurring under the influence of thermal and radiation effects in doped silicon (Fig. 3) [11,13-25].

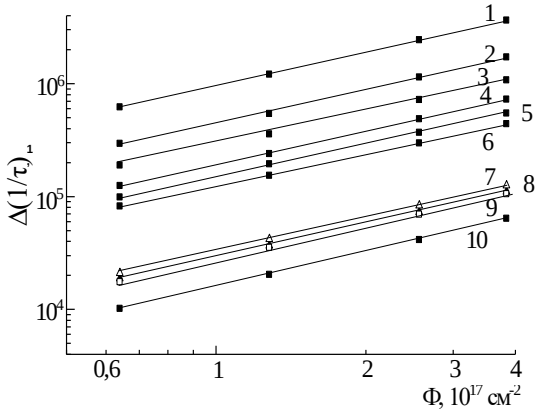


Fig. 2. dependence of the value Δ(1/τ) in p-Si<B> (1,2,) and p-Si<B, Ir> (3,4,5,6), as well as in p-Si<B, si> (7,8,9,10) in rapidly (2,4,6,8,10) and slowly (1,3,5,7,9) cooled samples on the dose of γ- radiation at different diffusion temperatures: 1-, 2- , 3-, 7- 1075 ℃; 4-, 8- 1175 ℃; 5-, 9- 1275 ℃; 6-, 10- 1285 ℃

Table-1. Parameters of doped and control p-type silicon before and after γ - radiation

A type samples	ρ, Ом·см	Тдиф., ℃	Cooling rate, deg / min	Ncu, см-3		τo, с	Kτ, см2/с
				Nобш.	Nакт.		
p-Si<B> p-Si<B> p-Si<Ir> p-Si<Cu>	10,2 10 9,7 9,6	1075	250 (II-type) 40 (I- type) 250 (II-type) 40 (I- type)	5·1017	2·1013 ≤1012	1·10-6 1,2·10-7 2·10-7 2,6·10-6	4,5·10-12 9,5·10-12 1,4·10-12 2,8·10-12

p-Si<B> p-Si<B> p-Si<Ir> p-Si<Cu>	12 10 9,1 8	1175	250 (II-type) 40 (I- type) 250 (II-type) 40 (I- type)	9·1017	4·1013 8·1013	7,9·10-7 1,4·10-6 3,2·10-7 4,5·10-6	3,9·10-12 9,1·10-12 1,2·10-12 1,9·10-12
p-Si<B> p-Si<B> p-Si< B,Ir> p-Si< B,Cu>	10,7 11 9,8 9,6	1275	250 (II-type) 40 (I- type) 250 (II-type) 40 (I- type)	1,2·10 18	6·1013 1014	4,6·10-7 1,6·10-6 5,9·10-7 6,8·10-6	3,1·10-12 4,5·10-12 2,9·10-13 3,3·10-13
p-Si<B,P,Ir> p-Si<B,P,Cu>	112 88	1285	250 (II-type) 40 (I- type)	1,8·10 18	2·1014 4·1014	7,3·10-7 9,2·10-6	1,5·10-13 2,7·10-13

In doped and control silicon, after exposure to penetrating radiation, the concentration of impurity [VM] and radiation (type A [VO] - and K [WOC]) centres, as well as compounds of the [MO] type, increases as a result of the radiation decay of clusters [MMM], silicides [IM], and SiOn -type compounds formed during high-temperature processing. This leads to an increase in the degree of micro-uniformity in conductivity in the doped samples compared to the control ones, so the Kτ values in the doped samples are lower than in the control ones. Part of thermo detection included two to four oxygen atoms [10-12, 23-25].

INFLUENCE OF γ-RADIATION ON THE LIFETIME OF CHARGE CARRIERS IN

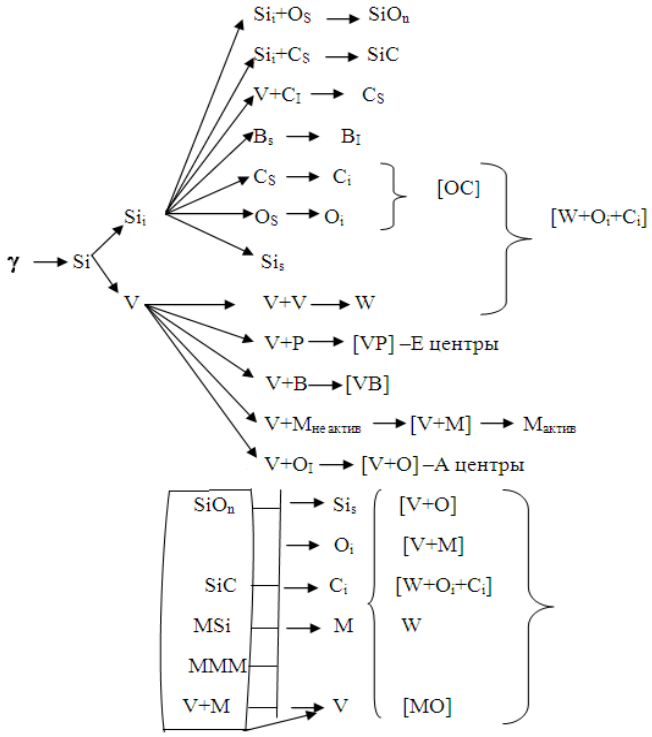


Figure 3. quasi-Chemical reactions of defect formation in doped Si: XS -, XI –impurity atoms in the node and in the internode; MMM-clusters; Sii-silicon atoms

in the internode; W-divacancy; MSI-silicides; M–impurity that creates deep energy levels; [W+O+C] – K-centre [8].

The interaction of these defects with vacancies increases the concentration of A-centres during irradiation. This can be described by the following scheme [15,16,21,22,24]:

$SiO4 + V \rightarrow SiO3 + A$– centre

$SiO3 + V \rightarrow SiO2 + A$ – centre

$SiO2 + V \rightarrow X$ – the centre

During irradiation, defects in doped silicon (clusters, silicides) move to a more equilibrium state, which is facilitated by both radiation - stimulated diffusion of impurities and the formation of a large number of vacancies and interstitial atoms. As a result, the probability of formation of impurity pairs such as CuO, Cu2O and IrSi increases. CuO, Cu2O electrically inactive defects, in turn, reduce the concentration of oxygen, which reduces the efficiency of the formation of A - and K-centres in doped silicon compared to the control and doped iridium (when the concentration of copper atoms is comparable to the concentration of oxygen atoms, the effect is more clearly manifested). Second, with an increase in the concentration of copper and iridium atoms, the micro-uniformity in conductivity in high-strength doped silicon increases. As a result of the influence of these two factors, the $K\tau$ value is effectively reduced in silicon doped with copper and iridium compared to the control one.

It is known that as the dose of gamma radiation increases, the micro-heterogeneity in conductivity and the concentration of recombination centres simultaneously increase [24-25]. As a result, the lifetime of charge carriers is limited by two recombination channels: the usual one - through the recombination centre (in this case, these are radiation centres) and the "barrier" one − with a probability of $1/\tau yrd$ and $1/\tau b$, respectively; therefore, $1/\tau yrd=\alpha\Phi$, i.e. proportional to the radiation dose (Φ). But the influence of recombination centres with increasing f is not observed until the equality is established: $1/\tau РЦ = 1/\tau b$. At $1/\tau РЦ = 1/\tau b$ the lifetime of non-basic charge carriers is stabilized in a certain range of the radiation dose.

CONCLUSIONS

The results of the study revealed specific patterns in the changes in charge carrier concentration and recombination properties of p-type silicon doped with copper and iridium under gamma irradiation. In particular, the relative change in charge carrier concentration in p-Si ⟨B,P,Cu⟩ and p-Si ⟨B,P,Ir⟩ samples was found to occur approximately twice as slowly as in control silicon. This behavior is attributed to the presence of several recombination mechanisms in doped silicon. Specifically, recombination through radiation-induced centers and recombination via the barrier mechanism interact and partially compensate for each other. As a result, the radiation stability of the material increases.

The study also established that an increase in the concentration of copper and iridium impurities in silicon leads to a decrease in the Kτ parameter. Furthermore, the Kτ values in copper- and iridium-doped silicon samples were found to be lower than those in control silicon. This phenomenon is associated with the formation and increased presence of microheterogeneities in the electrical conductivity of doped silicon. These microheterogeneities influence charge carrier transport and recombination processes within the material.

The obtained results demonstrate that the concentration of doping impurities plays an important role in controlling the electrophysical properties of silicon under radiation exposure. Moreover, taking into account the interaction between recombination centers and potential barriers provides a better understanding of the mechanisms responsible for the radiation stability of doped silicon.

Overall, the findings of this study are of scientific and practical importance for further investigation of recombination processes in copper- and iridium-doped silicon, evaluation of the radiation resistance of semiconductor materials, and the selection of promising materials for modern electronic devices operating under conditions of ionizing radiation.

Refenrence:

1. Milwidsky M. G.. Semiconductor silicon on the threshold of the XXI century // Materials of electronic equipment. 2000. - Issue 1. - Pp. 4-14.

2. B. I. Boltaks, M. K. Bahadyrkhanov, S. M. Gorodetsky, G. S. Kulikov / Compensated silicon/ - L.: Nauka, 1972. -124 p.

3. Konozenko I. D., Semenyuk A. K., Khivrich V. I. Radiation effects in silicon. - Kiev: Naukova Dumka, 1974. -199 p.

4. L. S. Smirnov, S. P. Solovyov, V. F. Stas, V. A. Kharchenko. Doping of semiconductors by the method of nuclear reactions / Response. edited By L. S. Smirnov. - Novosibirsk: Nauka, 1981, p. 181.

5. Mishanin A., Rodionov A., Barinov I., KozinS.. Semiconductor sensitive elements of pressure sensors based on nanostructured polycrystalline silicon / / Components and Technologies. 2009. No. 98. Pp. 29-32.

6. Barinov I. Dis. name of the candidate of technical Sciences. Protected 22.12.05. Penza. 2005.

7. Kobeleva S. P., Anfimov I. M., Shchemerov I. V., Kholodny L. P., Borzykh I. V., Ptashinsky V. V.. Standard samples of the lifetime of nonequilibrium charge carriers in single-crystal silicon // References. Standard sample. 2015. No. 1. P. 16-22.

8. A. A. Lebedev, V. V. Kozlovsky, etc. Radiation resistance of wide-band semiconductors. Physics and technology of semiconductors, 2002, volume 36, issue 11. Pp. 1354-1359

9. M. D. Varentsov, G. P. Gaidar, A. P. Dolgolenko, P. G. Litovchenko.. Radiation resistance of germanium-doped silicon with a high concentration of free oxygen. Nuclear Fizika TA Energetika. No. 1 (17) 2006. Pp. 60-66.

10. G. I. Zebrev. Radiation effects in high-integration silicon integrated circuits. National research nuclear University MEPhI, 2010, 148 p.

11. Bogatov N. M., Kovalenko M. S. Modeling of the kinetics of radiation defect formation in lithium-doped silicon // Izvestiyavuzov. North Caucasus region. Series: Natural Sciences. 2007. No. 1. Pp. 34-40.

12. Iles P. A. / / Solar Energy Materials And Solar Cells. 2001. Volume 68. # 1. Pp. 1-13.
13. hisamatsu T. and all. // Solar Energy Materials And Solar Cells. 1998. Volume 50. # 1-4. Pp. 331-338.
14. M. S. Yunusov, M. Karimov, R. N. Khamraeva, Kh. P. Kurbanov, M. N. Alikulov. The joint influence of doping with copper on the properties of sulphur and platinum in P-B1. 7/UFC. 1996. .4. P. 39-41.
15. M. S. Yunusov, M. Karimov, Djalilov M. A. To the question of the stabilization of electrical properties of compensated silicon under irradiation □-quanta 60Co // FTP. - Saint Petersburg, 2001. - Vol. 35. - Issue 3. - P. 317-320
16. Vinetsky V. L. Kholodar G. A. Radiation physics of semiconductors. Kiev: 1979, 1979. 336 P.
17. The mahkamah sh., Tashmetov M. Yu., Makhmudov sh. a., Rafikov A. K., A. A. Sulaimonov, Mirziraimov J. Z. Thermal stability of the lifetime of charge carriers in precompositional n-si<, C>. IX international conference "Modern problems of nuclear phisics nuclear technologies" in Tashkent, Uzbekistan 24-27 September 2019, P -221-223.
18. Glazov, V. M., and Timoshin, G. G., Mikhailov M. S. To the rationale for the selection of alloying additives to increase thermal stability of silicon. // Inorganic material. Moscow, 1997, Vol. 33, No. 6, Pp. 647-651.
19. K Abdurakhmanov. P., R Witman. f., X daliev.S., Lebedev A. A., Utamuradova sh. b. Investigation of the effect of □-irradiation on the properties of n-si<MN> using DLC // FTP. - Saint Petersburg, 1985. - Vol. 19. - No. 9. Pp. 1617-1619.
20. M. Yu. Tashmetov, Sh. A. Makhmudov, A. A. Sulaimonov, A. K. Rafikov, B. Zh. Abduraimov. Photodetectors based on silicon doped with neutrons / / ISSN 0003-701X, Applied solar energy, 2019, vol. 55, no. 1, Pp. 71-73. © Allerton Press, Inc., 2019.Russian text © author(s), 2019, published in Geliotekhnika, 2019, No.1, Pp. 83-85.
21. Yunusov M. S., Karimov M., Alikulov M. N., Begmatov K. Radiation-induced defect formation in p-type silicon doped with admixtures of transition elements. / Radiation effects and defects in solids. - Berlin, 2000. - V. 152. - P. 171-180
22. Pagava T. A. Features of annealing of radiation defects in irradiated p-si crystals. / / FTP. 2007, Volume 41. Issue 6. With 651-653.
23. Makhkamov Sh., Makhmudov Sh. A., Begmatov K. A., Rafikov A. K., Sulaimonov A. A., ErgashevKh. Collection of reports of the International conference "Modern materials and technologies". Tbilisi, Georgia 2015 October 21-23, P. 90-92.