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THERMAL AND RADIATION RESISTANCE OF CLUSTERS OF IMPURITY ATOMS IN SILICON

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Summary

This paper presents the results of a study of the effect of γ-irradiation and thermal annealing on the properties of silicon with nanoclusters of manganese atoms. It is shown that in the region of thermal annealing T≤120 °C, a significant change in the resistivity of silicon with manganese without clusters begins. At t=5 hours, the samples practically acquire their initial pre-diffusion parameters, i.e. there is an intensive decomposition of the Si<Mn> solid solution. It has been established that multiply charged nanoclusters decompose at lower radiation doses (>10^6R) due to the strong Coulomb interaction with vacancies.

Keywords: γ- irradiation, thermal annealing, silicon, manganese, doping, cluster, Coulomb force.

Резюме:

В данной работе представлены результаты исследования влияния γ-облучения и термоотжига на свойства кремния с нанокластерами атомов марганца. Показана, что в области термоотжига T≤120 °С начинается существенное изменение удельного сопротивления кремния с марганцем без кластеров. При t=5 часов, образцы практически приобретают свои исходные до диффузионные параметры, т.е. происходит интенсивный распад твердого раствора Si<Mn>. Установлено, что многозарядные нанокластеры распадаются при более низких дозах облучения (>10^6Р) из-за сильного кулоновского взаимодействия с вакансиями.

Rezyume:

Ushbu ishda marganets atomlarining nanoklasterlari hosil qilingan kremniy xossalariga γ-nurlanish ta'sirini urganish natijalari keltirilgan. T≤120 °C termik

kuydirish chegarasida kremniyning marganets bilan legirlangan klastersiz namunalarida solishtirma qarshiligi sezilarli o'zgarib boshlashi ko'rsatilgan t= 5 soat mobaynida kuydirilganda namunalar diffuziyadan oldingi dastlabki parametrlariga kelib qoladi, yani Si<Mn> qattiq qotishmasidagi kirishmaning intensiv parchalanishi ruy beradi. Ko'p zaryadlangan nanoklasterlar katta doza (>10^6R) nurlanishida Kulon kuchining o'zaro vakansiyalar bilan tasirlashishida parchalanishi aniqlangan.

Kalit so'zlar: γ-nurlanish, termik kuydirish, kremniy, marganets, legirlangan, klaster, Kulon kuchi.

Ключевые слова: γ-облучение, термоотжиг, кремний, марганец, легирование, кластер, сила Кулона.

Introduction

The phenomenon of interaction of impurity atomic clusters with crystal lattice defects is by its nature a new type of interaction. In contrast to the interaction between point defects, which result in the formation of various point complexes, in the case under consideration, it is necessary to take into account the behavior of point defects in the region of sufficiently strong deformation, electric, and magnetic potentials created by clusters. As point defects, we chose radiation defects created by γ-irradiation, thermal defects generated in the low-temperature region, as well as multiply charged impurity atoms (S^+, S^{++},Se^+, Se^{++}). As clusters, we studied clusters of nickel atoms, as well as multiply charged clusters of manganese atoms in silicon.
The study of the interaction between clusters and point defects with different nature makes it possible not only to evaluate the stability of the state of clusters under radiation exposure and heat treatments, but also the possibility of obtaining information about the degradation and decay of clusters.
Clusters of impurity atoms can be electrically neutral and multiply charged, as well as magnetic. Therefore, depending on the charge state of point defects, the interaction between defects and clusters of different nature makes it possible to obtain additional information about the nature of the potentials created by impurity atomic clusters.
Nanoclusters of manganese [1÷3] atoms in the Si lattice can be considered as quantum dots. Therefore, the interaction of defects with quantum dots is of certain scientific and practical interest.
In this paper, we consider the interaction of clusters of nickel atoms and nanoclusters of manganese atoms with radiation defects formed during γ - irradiation, with thermal defects, etc.

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As is known [4÷7], γ – irradiation in silicon produces primary radiation defects, such as vacancies (V) and interstitial atoms, as well as A – centers. And with an increase in the dose of radiation, i.e. when the concentration of such defects increases, secondary radiation defects can form. These are divacancies (V_2), trivacancies (V_3), vacancy pores, and, accordingly, various complexes of interstitial silicon atoms. Depending on the position of the Fermi level in the original silicon, radiation defects can act as electrically neutral, singly, doubly charged (V^o, V^-, V^{--}), etc. Therefore, it is very important to study the interaction of clusters with radiation defects in silicon, depending on the position of the Fermi level.

It was shown in [8] that the doping of silicon by the "low-temperature" doping method makes it possible to form nanoclusters of manganese atoms. In these works, using the electron paramagnetic resonance (EPR) method, as well as AFM, it was unambiguously established that such clusters consist of four positively charged manganese atoms located in the nearest equivalent interstitial positions around the negatively charged boron atoms. It was also found that the size of such nanoclusters is 2÷3 nm, and depending on the doping conditions, they can be in different charge states (from +3÷+7), their structure has the form $\left[\left(Mn^1\right)_4^{+n}B^{-1}\right]^{+(n-1)}$. It is shown that the manganese atoms involved in cluster formation have the electronic structure $3d^54s^1$ or $3d^54s^0$, therefore, such clusters also have sufficiently powerful magnetic moments. Thus, unlike clusters of nickel atoms, clusters of manganese atoms are not only nanoscale, but also multiply charged and magnetic.

Therefore, it is of great interest to study the influence of γ-irradiation and low-temperature annealing, since, firstly, such studies will make it possible to elucidate the interaction of radiation and thermal defects with multiply charged and magnetic clusters that create a sufficiently strong electric and magnetic field around them, and, secondly, to evaluate the radiation and thermal stability of silicon properties with manganese nanoclusters. As shown in such materials, a number of new physical phenomena are observed, for example, an anomalously high negative magnetic resistance at T=300 K, and a giant impurity photoconductivity in the region of λ=1,5÷8 μm, on the basis of which new electronic devices can be created.

The effect of γ-irradiation of the Co^{60} isotope was studied in samples in which anomalously high NMR, impurity and residual photoconductivity were found. In these samples before irradiation, an EPR spectrum consisting of 21-lines was clearly revealed, indicating the presence of nanoclusters of manganese atoms $[Mn]_4$[32, 88, 105], and all of the above very interesting phenomena were found in them. Samples with nanoclusters were subjected to irradiation, as well as samples with similar

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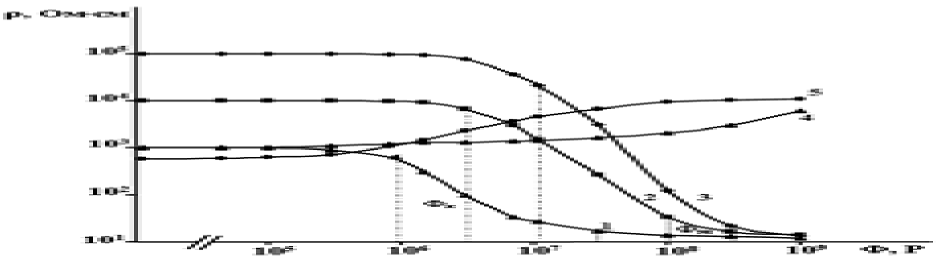
parameters doped with manganese without nanoclusters and samples without manganese with the same parameters. After each stage of irradiation, the electrical and magneto-photoelectric properties of the samples were studied under identical conditions.

As the results of the study showed, there is a critical dose of irradiation (Φ_k) at which the electrical parameters, as well as the magneto-photoelectric properties of silicon samples with nanoclusters, change significantly. The value of $\Phi_к$ depends on the multiplicity of the charge state of the nanoclusters and, $\Phi_к$ with a decrease in the latter, shifts towards higher irradiation doses (Fig. 1, curves 1÷3).

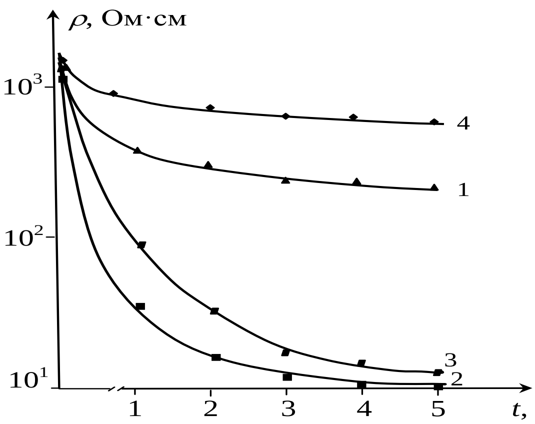
With a further increase in the irradiation dose to fm, the specific resistance of the samples decreases significantly to ρ=10÷15 Ohm·cm, i.e. the samples practically acquire the initial parameters of p-type silicon before the diffusion of manganese. The value of $\Phi_м$ also increases with a decrease in the charge multiplicity of nanoclusters (Fig. 1, curves 1÷3). At the same time, the effect of γ-irradiation on the electrical parameters of manganese-doped silicon samples without nanoclusters, as well as on control samples, has a different character (Fig. 1, curves 4, 5). As can be seen from the figure, in these samples, a noticeable change in resistivity begins at sufficiently high doses $(\Phi \geq 10^8 P)$, and with an increase in the irradiation dose, the resistivity does not decrease, as in the case of samples with nanoclusters, but increases to the value of intrinsic silicon.

The study showed that the intensity of the EPR spectra associated with manganese nanoclusters weakens with an increase in the irradiation dose, and at a dose of 10^6 R it is practically not observed, instead of them there appear spectra consisting of six lines associated with individual manganese atoms in the $3d^54s^0$ state. These research results show that when irradiated with γ-quanta with a dose of $\Phi \geq 10^6$ R, nanoclusters are destroyed and their the concentration becomes so small that their effect on the EPR spectrum is not noticeable.



Picture 1. Dependence of the resistivity of the samples on the dose γ - irradiation. 1, 2, 3 - Si<B,Mn> (p-type) with nanoclusters with charge state multiplicity +7,+5,+3, respectively, 4 - control sample, 5 - Si<B,Mn> (p-type) without nanoclusters.

We also studied the effect of low-temperature annealing on the properties of silicon with manganese clusters, as well as manganese-doped silicon without cluster formation (alloying by high-temperature annealing) with the same electrical parameters and with the same concentration of introduced manganese atoms. As is known, radiation defects in the form of vacancies and interstitial atoms of the base material are created in the process of irradiation. As the radiation dose increases, their concentration increases. This leads to the appearance of divacancies, various complexes with other lattice defects, and, at high doses, to the creation of vacancy pairs and clusters of interstitial atoms [9, 10].



Picture. 3.11. Influence of low-temperature annealing on the state of clusters of impurity manganese atoms in Si<B,Mn> samples with ($\rho=7\div8\cdot10^3$, p-type).
1. T≥150 °C for samples without clusters, 2. T≤150 °C for samples without clusters
3. T≥ 200 °C for samples with clusters, 4. T≤200 °C for samples with clusters

With increasing temperature, this process accelerates significantly (Pic. 3.11 curves 1, 2), which coincides with the results of the authors' work [11]. In contrast to such samples, in samples with nanoclusters practically up to T≤120 °C (Pic. 3.11 curve 4) there is no noticeable change in electrical parameters and the NMR phenomenon and high photosensitivity in the region λ=1,5÷8 μm are observed in them. As the annealing temperature increases, their properties also change. With the duration of annealing (t=3÷5hours), the samples acquire their original parameters, i. e. the disappearance of clusters and their decay (Pic. 3.11 cr.3).
It has been established that multiply charged nanoclusters decompose at lower radiation doses (>10^6R) due to the strong Coulomb interaction with vacancies.

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