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THERMAL AND RADIATION RESISTANCE OF CLUSTERS OF IMPURITY MANGANESE ATOMS IN SILICON

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Abstract. In this work, it was found that under the action of gamma radiation with a dose of $\Phi > 10^6$ R and a thermal annealing temperature of T<120 ^{0}C, clusters of manganese atoms disintegrate and the anomalous photo and magnetic properties manifested by clusters of manganese atoms disappear.

Keywords. Silicon, impurity cluster, gamma-irradiation, thermal combustion, diffusion, manganese, nanocluster, negative magnetoresistance, positive magnetoresistance.

I. Introduction.

The phenomenon of interaction of clusters of impurity atoms 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 this case 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 selected radiation defects created by γ-irradiation, thermal defects generated in the low-temperature region, and multiply charged impurity atoms (S^+, S^{++},Se^+, Se^{++}). Multiply charged clusters of manganese atoms in silicon were studied as clusters.

Investigation of the interaction between clusters and point defects of different natures makes it possible not only to assess the stability of the state of clusters under radiation exposure and heat treatment, but also to obtain information on the degradation and decay of clusters.

Clusters of impurity atoms can be electrically neutral multiply charged, as well as magnetic. Therefore, depending on the charge state of point defects, the interaction between defects and clusters of different natures allows one to obtain additional information on the nature of the potentials created by clusters of impurity atoms.

Nanoclusters of manganese atoms [1÷2] 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.

As is known [3÷4], γ-irradiation creates primary radiation defects in silicon, such as vacancies (V) and interstitial atoms, as well as A - centers. And with an increase in the radiation dose, i.e. when the concentration of such defects increases, secondary radiation defects can form. These are divacansions (V_2), three vacancies (V_3), vacancy pores, and, accordingly, various complexes of interstitial silicon atoms. Depending on the position of the Fermi level in the initial silicon, radiation defects can act as electroneutral, single, double charged (V^0, 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.

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In [5], it was shown that the doping of silicon by the method of "low-temperature" doping allows the formation of nanoclusters of manganese atoms. In these studies, the electron paramagnetic resonance (EPR) and AFM methods unambiguously established (Fig.1,2) that such clusters consist of four positively charged manganese atoms located in the nearest equivalent interstitial positions around the negatively charged boron atom. 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 following 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 an electronic structure of $3d^5 4s^1$ or $3d^5 4s^0$, so such clusters also have sufficiently powerful magnetic moments. Thus, unlike clusters of nickel atoms, clusters of manganese atoms are not only nanoscale, but are also multi-charged and magnetic.

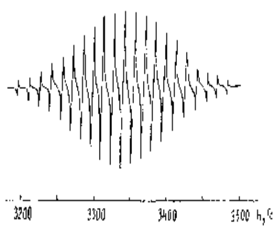

Figure 1. EPR spectrum of nanoclusters of manganese atoms in silicon

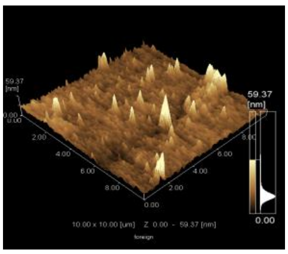

Fig. 2. Image of nanoclusters of manganese atoms in silicon, obtained on the AFM

Therefore, it is of great interest to study the effect of γ - irradiation and low-temperature annealing, since, firstly, such studies will allow us to find out the interaction of radiation and thermal defects with multicharged and magnetic clusters that create a sufficiently strong electric and magnetic field around them, and secondly, to evaluate the radiation and thermal stability of the properties of silicon with manganese nanoclusters. As it was shown in such materials, a number of new physical phenomena are observed, for example, an abnormally 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 Co^{60} isotope γ - irradiation was studied in samples with abnormally high NMR, impurity and residual photoconductivity. In these samples, before irradiation, the EPR spectrum consisting of a 21-line was clearly detected, indicating the presence of nanoclusters of manganese atoms [6], and all the above-mentioned very interesting phenomena were found in them. Samples with nanoclusters, as well as samples with similar parameters, doped with manganese, without nanoclusters, and samples without manganese with the same parameters were irradiated. After each stage of irradiation, the electrical and magneto - photovoltaic properties of the samples were studied under identical conditions.

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

With a further increase in the radiation dose to Fm, the resistivity of the samples significantly decreases 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 Φ_M value also increases with a decrease in the charge multiplicity of nanoclusters (Fig. 3 curves 1÷3). At the same time, the effect of γ-irradiation on the electrical parameters of samples of silicon doped with manganese without nanoclusters, as well as on control samples, has a different character (Fig. 3, curves 4, 5).

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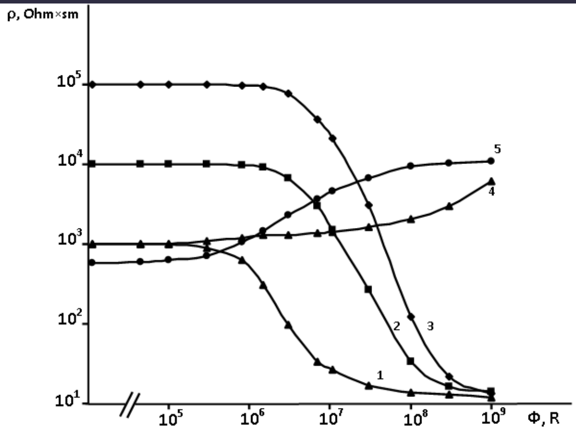


Fig. 3. Dependence of the resistivity of the samples on the dose

γ - irradiation.

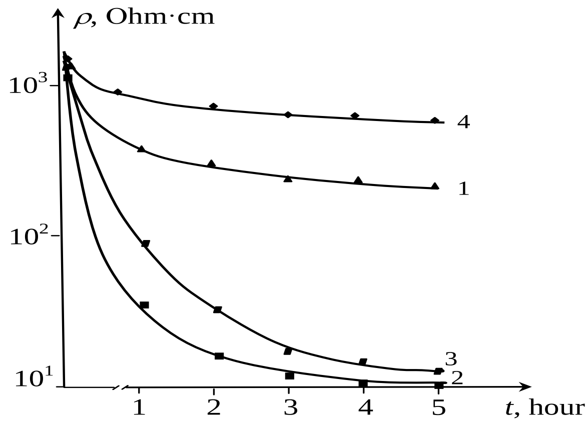
1, 2, 3 - Si <B,Mn> with nanoclusters with a charge state multiplicity of + 7, + 5, + 3, respectively, *4* - control sample, *5*- Si <B,Mn> without nanoclusters.

As can be seen from the figure, in these samples, a noticeable change in the resistivity begins at sufficiently high doses $(\Phi \geq 10^8 R)$, and with an increase in the radiation dose, the resistivity does not decrease, as in the case of samples with nanoclusters, but increases to the value of its own silicon.

The study showed that the intensity of the EPR spectra associated with manganese nanoclusters weakens with an increase in the radiation dose, and at a dose of 10^6 R is practically not observed, in their place there are 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 concentration becomes so small that their effect on the EPR spectrum is not noticeable.

We also investigated the effect of low-temperature annealing on the properties of silicon with manganese clusters, as well as manganese-doped silicon without clusters (doping by high-temperature annealing) with the same electrical parameters and with the same concentration of introduced manganese atoms. It is established that in the area of thermal ignition T≤150°C begins a significant change in the resistivity of silicon with manganese without clusters. At t=5 hours, the samples practically acquire their initial pre-diffusion parameters, i.e., an intensive decomposition of the Si<Mn > solid solution occurs. With increasing temperature, this process is significantly accelerated (Fig. 4. curves 1, 2), which coincides with the results of the authors ' work. In contrast to such samples, in samples with nanoclusters almost up to T≤150 °C (Fig. 4 cr. 4) there is no noticeable change in the electrical parameters and the phenomenon of NMR and high photosensitivity in the region λ=1,5÷8μm is observed in them. As the annealing temperature increases, their properties also change. At the annealing time (t=3÷5 hours), the samples acquire their original parameters, i.e., the clusters disappear and their decay occurs. (fig. 4 cr. 3)



4. Effect of low-temperature annealing on the state of clusters of impurity manganese atoms in Si<B,Mn> c (ρ=7÷8·10^3, p - type) samples.

1. T≥150 °C for samples without clusters

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2. T≤150 °C for samples without clusters

3. T≥ 200 °C for samples with clusters

4. T≤200 °C for samples with clusters

As is known, radiation defects in the form of vacancies and interstitial atoms of the base material are created during the irradiation process. As the radiation dose increases, their concentration increases. This leads to the appearance of divacancy, various complexes with other lattice defects, and at high doses to the creation of vacancy pairs and clusters of interstitial atoms.

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