Influence of γ – radiation on the properties of silicon with clusters impurity atoms of manganese and nickel

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Abstract. In works [1-4], it was shown that a number of new physical phenomena are observed in silicon with nanoclusters, such as high-temperature negative magnetoresistance (NMR), anomalously high impurity photoconductivity, giant residual photoconductivity, etc. All these phenomena are directly related to the presence of multiply charged, magnetic clusters of manganese atoms in the silicon lattice. It is shown that, on the basis of such materials, it is possible to create fundamentally new, highly sensitive magnetosensors, photodetectors of infrared radiation operating in the μm region and photomagnetic devices.

1 Introduction

As is known [5], g-irradiation in silicon creates primary radiation defects, 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 divacancies (V₂), trivacancies (V₃), 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 electrically neutral, singly, doubly charged (V⁰, 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 [1-4].

This paper presents the results of a study of the effect of γ-irradiation on the properties of silicon with nanoclusters of manganese atoms. Such studies are of interest, on the one hand, for clarifying the features of radiation-induced defect formation and the interaction of defects with multiply charged clusters, and, on the other hand, for assessing the radiation resistance of such materials and devices based on them.

The influence of γ-irradiation of Co⁶⁰ was studied in samples in which anomalously high NMR, impurity and residual photoconductivity were found. In these samples, before irradiation, the EPR spectrum consisting of 21 lines was clearly revealed, indicating the presence of nanoclusters of manganese atoms [6-7], and all of the above interesting phenomena were also 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-photoelectric properties of the samples were studied under identical conditions.

2 The mathematical statement of the problem

As shown by the results of the study, there is a critical radiation dose at which the electrical parameters, as well as the magneto-photoelectric properties of silicon samples with nanoclusters, change significantly. The value of Φₓ depends on the multiplicity of the charge state of nanoclusters and, with a decrease in the latter, shifts towards higher doses (Fig. 1, curves 1-3). With a further increase in the irradiation dose to Φₓ, the resistivity of the samples significantly decreases to ρ= 10⁻¹⁵ Ohm×sm, i.e. the samples practically acquire the initial parameters of p-type silicon before the diffusion of manganese. The value of Φₓ also increases with decreasing multiplicity of the charge of nanoclusters (Fig. 1, curves 1-3). At the same time, the effect of γ-irradiation on the electrical parameters of silicon samples doped with manganese without nanoclusters, as well as on the 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 the resistivity begins at sufficiently high doses, 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 [8-14].

Figure 2. the effect of γ-irradiation on the value of magnetoresistance in the samples is presented. As can be seen, starting with a dose, the value of the NMR in the samples with nanoclusters sharply decreases, and at Φ = Φₓ, the sign of the magnetoresistance (MR) is inverted from NMR to positive magnetoresistance (PMR). With a further increase in the irradiation dose, the PMR value increases slightly (curve 1).
samples with a dose of $\Phi \geq 10^7$ R, the X-ray spectra associated with nanoclusters of manganese atoms are not observed, but there is a spectrum associated with the state of manganese atoms $\text{Mn}^0$ and $\text{Mn}^-$. The obtained experimental data can be explained by the strong electrostatic interaction of radiation defects with multiply charged nanoclusters. As was shown in [2,3], when silicon is doped with manganese by the "low-temperature diffusion" method, almost all introduced manganese atoms participate in the formation of clusters. One of the main requirements for cluster formation is the presence of manganese atoms in the lattice in the $\text{Mn}^+$ and $\text{Mn}^{++}$ states. Nanoclusters in the silicon crystal lattice consist of $4$-manganese atoms in the nearest interstitial states around a negatively charged boron atom $[(\text{Mn})_4^+\text{B}^{1-}]^{0_{-1}}$ [5-9].

The multiplicity of the charge of nanoclusters, depending on the ratio of the concentrations of boron and manganese atoms, varies in the range from +3 to +7. Therefore, around such clusters there is a sufficiently strong electric potential, the value of which depends on the multiplicity of the charge of the nanoclusters. If we take into account that the vacancies formed as a result of irradiation have a sufficiently large diffusion coefficient, low migration energy $\Delta E \approx 0.3 \beta$, [10÷12] and can be in the lattice in a single and double negatively charged state, then the interaction between vacancies and nanoclusters will be the determining factor in the formation of a defect structure in such materials. As a result of the interaction, vacancies can capture manganese atoms ($\text{Mn}^+$, $\text{Mn}^{++}$), and this leads to the decomposition of nanoclusters and the formation of a manganese atom in the lattice sites in the form of an acceptor impurity atom. At the initial stage of irradiation ($\Phi < \Phi_k$), when the concentration of vacancies is less than the concentration of nanoclusters, the properties of the material are determined by nanoclusters. When the vacancy concentration becomes comparable to the concentration of nanoclusters, the nanoclusters disintegrate and the properties of the material are determined by the properties of manganese atoms located at the sites of the crystal lattice and by the concentration of boron atoms. The discovery of the electric levels created by manganese atoms at the lattice sites was not crowned with success. This may be due to the high ionization energy of the manganese acceptor levels, as well as the effect of a sufficiently high concentration of holes in the valence band [31-35].

3 Conclusions

The results obtained suggest that the formation of nanoclusters of manganese atoms not only significantly increases the photosensitivity of silicon in the impurity region, leads to the formation of an anomalously high NMR, but also controls the accumulation of radiation defects in the region of high radiation doses. This means that by creating nanoclusters based on manganese atoms in silicon with p-type conductivity, it is possible to obtain a radiation-resistant material for the region of high irradiation doses $\Phi > \Phi_k$, while maintaining its initial parameters measured before the formation of nanoclusters. It should also be noted that the magnetic and electrical properties of silicon with nanoclusters are sufficiently stable up to an irradiation dose of $\Phi = 10^9 \times 10^7$ R, and devices based on such materials also do not change their parameters at high irradiation doses.
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