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STUDY OF THE FORMATION OF RADIATION DEFECTS IN IRRADIATED SILICON SAMPLES, DOPED WITH CHROMIUM ATOMS

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This work presents an investigation of radiation-induced defect formation in single-crystal n-type silicon doped with chromium (n-Si<Cr>) using positron annihilation spectroscopy. The initial silicon samples, phosphorus-doped during crystal growth, were subsequently modified by chromium diffusion and then irradiated with 2 MeV protons at a beam current of 0.5 μA using the EG-5 accelerator facility. The measurements revealed the formation of characteristic radiation-induced vacancy-type defects, including A-centers, E-centers, divacancies, and their stable complexes. A comparative analysis of chromium-doped and undoped samples demonstrated a pronounced difference in the accumulation rate of these defects. It was established that the presence of chromium atoms in the bulk of n-type silicon significantly suppresses radiation defect formation: the concentration of vacancy-related defects in n-Si<Cr> was found to be approximately 1.5–2 times lower than in the reference n-Si samples irradiated under identical conditions. These results confirm that chromium doping enhances the radiation resistance of silicon and can be considered an effective approach for modifying semiconductor materials intended for operation in environments with high radiation exposure.

Keywords: *Semiconductor; Silicon; Chromium; Doping; Irradiation; Proton; Positron annihilation*
PACS: 78.30. Am

INTRODUCTION

The complex theoretical and practical research on semiconductor materials is of great interest to researchers [1-3]. As a result of research, various diode structures and devices based on them can be seen [4-7].

The study of radiation-induced defects in silicon (Si) and doped silicon materials is an important direction in modern semiconductor science and technology. Under proton irradiation, atoms of the crystal lattice are displaced from their lattice sites, leading to the formation of vacancies, interstitial atoms, and their complexes. These defects have a significant impact on the electronic properties of the material, including electrical conductivity, charge carrier concentration, and electron mobility, which are directly related to the functional characteristics of semiconductor devices, especially those operating under extreme radiation conditions [8-10].

Of particular interest are doped silicon systems such as n-Si<Cr>, where the presence of chromium impurities can substantially alter the formation and evolution of radiation defects. Impurities can interact with vacancies and interstitial atoms, promoting the formation of complex defects with different energy characteristics and enhanced stability. This makes doped materials especially attractive for studies aimed at improving the radiation hardness of semiconductor devices [11, 12].

A key tool for investigating such defects is positron annihilation spectroscopy (PAS), which provides high sensitivity to vacancies and their complexes. This method allows not only the quantitative determination of defect concentrations but also the characterization of their nature and size, as well as the evaluation of the dynamics of changes in the crystal structure under proton irradiation. Owing to these capabilities, PAS has become a standard technique for studying radiation effects in semiconductors [13].

The comprehensive use of experimental data makes it possible to obtain a deep understanding of the processes of formation and evolution of radiation defects in n-Si and n-Si<Cr>. Analysis of the obtained results provides not only fundamental knowledge about the interaction of protons with the crystal lattice but also practical information for the development of semiconductor materials with enhanced resistance to ionizing radiation. These data are of great importance for space electronics, nuclear power engineering, and other fields where the reliability of semiconductor devices critically depends on their radiation stability [14].

The aim of the present work is to study radiation-induced defect formation in n-Si and n-Si<Cr> silicon single crystals using positron annihilation spectroscopy.

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In solid-state spectroscopy, once a positron has thermalized, it is treated as a point-like particle that remains within the solid until it annihilates or becomes trapped. During its lifetime in the lattice, the positron diffuses through the crystal, tending to avoid the positively charged atomic nuclei and therefore occupying interstitial regions. Because the positron wave function becomes strongly localized at defect sites, changes in defect structure can be qualitatively inferred from the S–W plot, as discussed in Refs. [15, 16]. However, direct comparison of absolute S and W parameters obtained from different spectrometers is discouraged, since these values are influenced by the instrument's energy resolution and the specific window settings used during their evaluation (Fig. 1).

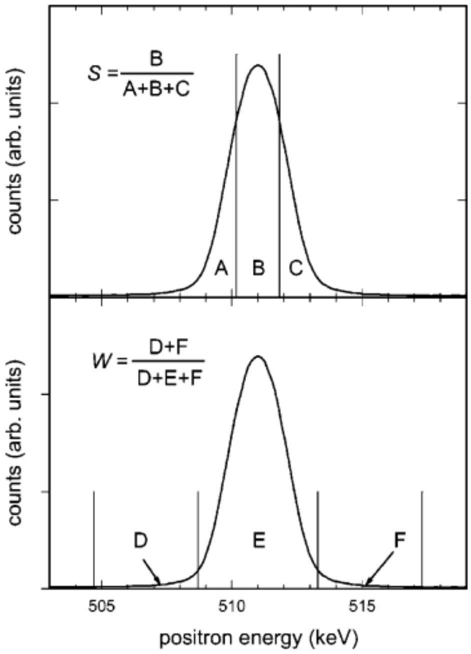

Figure 1. Dependence of parameters S and W on the positron energy with corresponding energy windows, used in the analysis of the positron annihilation peak at 511 keV

EXPERIMENTAL PART

The samples investigated in this study were n-type silicon wafers (KEF-20) with dimensions of 1.5×7×14 mm and a resistivity of 20 Ω·cm. These wafers were obtained from silicon single crystals grown by the Czochralski technique. Chromium was introduced into the silicon by diffusion, using a metallic chromium layer deposited on the wafer surface and sealed in evacuated quartz ampoules. The diffusion process was carried out at 1200 °C for 2 hours, followed by cooling according to the thermal treatment procedures described in Refs. [17, 18]. The concentration of phosphorus dopant in the initial n-type silicon crystals was 4.5×10^{14} at/cm^3.

After surface cleaning, the chromium-doped silicon samples were irradiated with 2 MeV protons at a beam current of 0.5 μA to achieve a total fluence of 5.1×10^{14} particles/cm^2. The irradiation procedures were performed using the "EG-5" electrostatic accelerator at the Frank Laboratory of Neutron Physics (FLNP), Joint Institute for Nuclear Research (JINR).

Radiation-induced structural defects in the samples were examined using positron annihilation spectroscopy, specifically by analyzing the Doppler broadening of the 511 keV gamma line. The measurements were conducted using a positron beam facility with adjustable implantation energy for depth profiling, located at the Laboratory of Nuclear Problems, JINR.

RESULTS AND DISCUSSIONS

Figure 2 illustrates the variation of the S parameter as a function of positron implantation energy for n-Si and n-Si<Cr> samples following proton irradiation at room temperature. A distinct increase in the S parameter is observed in the shallow region corresponding to positron energies of 0.1–2 keV (Fig. 2, curve 1). For positron energies in the range of 3–17 keV, which probe deeper into the samples, the S parameter decreases below its initial value in the irradiated n-Si. Previous studies [19] on irradiated n-Si and n-Si<Pt> demonstrated that positron annihilation behavior differs significantly between n-Si<Cr> and n-Si<Pt> samples, indicating a dependence on the impurity type of doping.

The S parameter of the irradiated n-Si<Cr> sample is lower than that of the irradiated n-Si sample (Fig. 2, red curve). An increase in S is observed in the shallow region corresponding to positron energies of 0.05–1.8 keV. At greater depths, corresponding to implantation energies of 1.8–23 keV, the S parameter falls below the bulk value.

The S parameter reflects the fraction of positron annihilations occurring with valence electrons [20]. In these materials, it is also necessary to consider the contribution of positronium annihilation, which can affect the measured S values. However, the influence of parapositronium annihilation can be accounted for by comparing S with the W parameter, which represents positron annihilation with core (nuclear) electrons. In the absence of parapositronium effects, the S and W profiles should exhibit opposite trends, as illustrated in Fig. 3.

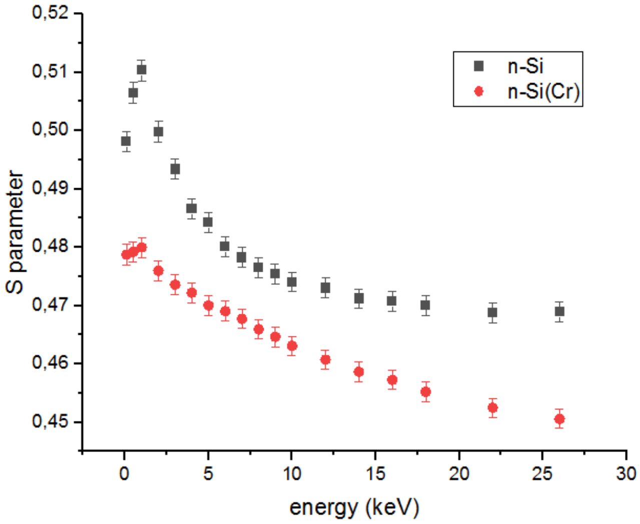

Figure 2. Variation of the S parameter as a function of positron implantation energy (corresponding depth) for irradiated silicon samples: n-Si (1) and n-Si<Cr> (2)

When comparing n-Si and n-Si<Cr>, it is evident that defect concentration decreases with increasing positron energy, indicating that defects are more prevalent near the surface. In Fig. 2, the implantation profiles suggest partial "healing" of defects throughout the depth of n-Si. In contrast, the n-Si<Cr> samples display both radiation-induced defects and additional structural defects caused by mechanical stress, which are more clearly reflected in the S parameter.

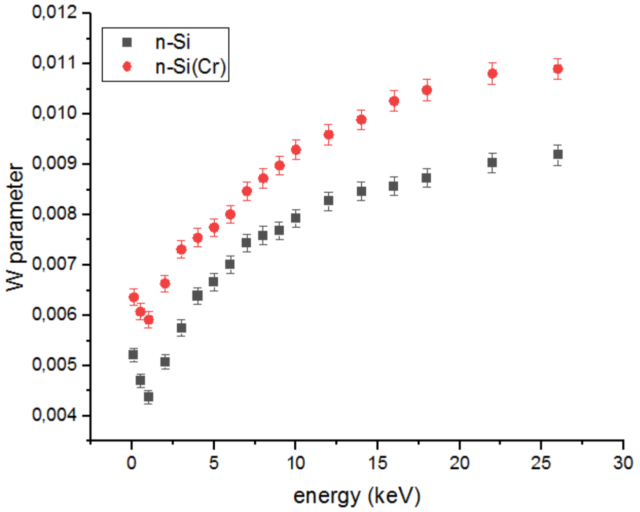

Figure 3. Variation of the W parameter as a function of positron implantation energy (corresponding depth) for irradiated silicon samples: n-Si (1) and n-Si<Cr> (2)

It is well established [21, 22] that the primary effect of radiation on semiconductors is the formation of radiation-induced defects, particularly vacancies. These defects commonly include oxygen-vacancy complexes (Oi–V, A-centers), divacancies (V–V), and phosphorus-vacancy complexes (P_S–V, E-centers).

Doping of monocrystalline silicon with chromium significantly affects the behavior of radiation-induced defects formed during proton irradiation. In particular, the presence of Cr atoms contributes to a reduction in the concentration of key point defects, such as A-centers, E-centers, and divacancies. This effect is achieved through the formation of stable "defect–Cr" complexes, which hinder the migration and aggregation of vacancies and interstitial silicon atoms, while also accelerating the recombination of free vacancies and interstitials. Thus, Cr simultaneously acts as a "trap" for radiation defects and a catalyst for their annihilation, leading to decrease in defect concentration compared to initial silicon and enhancing the material's radiation tolerance [23].

As noted in [24], real solids always contain some intrinsic defects, which disrupt the perfect translational symmetry of the lattice and the electronic band structure. In such regions, the local potential for positrons can decrease significantly, allowing individual positrons to become trapped. This trapping typically occurs at open-volume defects, such as vacancies, vacancy clusters, dislocations, and certain types of precipitates. Positrons can also localize near negatively charged foreign atoms (planar traps), although this effect is mainly observed at low temperatures due to minor reductions in positron potential. Additionally, vacancies in semiconductors can carry an electric charge, creating a long-range potential that attracts or repels positrons.

According to [25], open-volume defects exhibit a lower local electron density than an ideal crystal because atomic cores and core electrons are absent. Consequently, the positron annihilation rate decreases in these regions. Positron annihilation techniques generally assume that a positron trapped in a specific defect interacts primarily with the electrons in that defect. This interaction determines a characteristic annihilation probability, the reciprocal of which defines the positron lifetime in the defect. The lifetime describes how long positrons remain in a particular defect type before annihilation.

The small spatial extent of deep traps restricts the number of positron states that can be occupied and limits capture according to energy selection rules. In larger or more extended defect centers, capture is mainly limited by positron diffusion. Measurable positron trapping occurs only if defects are sufficiently dense; the average distance between defects of the same type must be smaller than the positron diffusion length in a defect-free lattice. As the density of defects increases, the S parameter correspondingly rises due to enhanced positron localization [26].

Based on these studies [21–27], it can be inferred that proton irradiation at 2 MeV generates radiation defects in both n-Si and n-Si<Cr> samples, predominantly associated with vacancies (A-centers, E-centers, divacancies, etc.). However, the concentration of vacancy-related defects in irradiated n-Si is approximately 1.5 times higher than in irradiated n-Si<Cr>. This indicates that chromium doping reduces the formation of radiation defects in the silicon lattice.

CONCLUSIONS

Positron annihilation spectroscopy measurements have shown that irradiation with 2 MeV protons at a fluence of 5.1×10^{14} cm^{-2} leads to the formation of vacancy-type radiation defects in both n-Si and n-Si<Cr> samples, including A-centers, E-centers, divacancies, and their complexes. However, a comparative analysis revealed a pronounced difference in defect concentration: in undoped n-Si, the density of these defects after irradiation is nearly 1.5 times higher than in chromium-doped n-Si samples.

This observation indicates that chromium atoms play a stabilizing role in the silicon crystal lattice, effectively reducing the accumulation of radiation-induced damage. Chromium doping partially suppresses the formation of vacancy-related complexes, thereby enhancing the radiation tolerance of the material.

Overall, the present results demonstrate the strong potential of chromium-doped silicon for use in microelectronic devices and structures intended to operate in high-radiation environments. These findings also contribute to a deeper understanding of radiation damage mechanisms in doped semiconductors and open new prospects for the development of more reliable and radiation-resistant semiconductor technologies.

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ДОСЛІДЖЕННЯ УТВОРЕННЯ РАДІАЦІЙНИХ ДЕФЕКТІВ В ОПРОМЕНЕНИХ ЗРАЗКАХ КРЕМНІЮ, ЛЕГОВАНИХ АТОМАМИ ХРОМУ

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У цій роботі представлено дослідження радіаційно-індукованого дефектоутворення в монокристалі n-типу кремнію, легованого хромом (n-Si<Cr>), за допомогою позитронно-анігіляційної спектроскопії. Вихідні зразки кремнію, леговані фосфором під час росту кристалів, згодом модифікували дифузією хрому, а потім опромінювали протонами з енергією 2 МеВ при струмі пучка 0,5 мкА за допомогою прискорювальної установки EG-5. Вимірювання виявили утворення характерних радіаційно-індукованих дефектів вакансійного типу, включаючи A-центри, E-центри, дивакансії та їх стабільні комплекси. Порівняльний аналіз легованих хромом та нелегованих зразків продемонстрував помітну різницю в швидкості накопичення цих дефектів. Було встановлено, що присутність атомів хрому в об'ємі n-типу кремнію значно пригнічує радіаційне дефектоутворення: концентрація дефектів, пов'язаних з вакансіями, в n-Si<Cr> виявилася приблизно в 1,5–2 рази нижчою, ніж у еталонних зразках n-Si, опромінених за ідентичних умов. Ці результати підтверджують, що легування хромом підвищує радіаційну стійкість кремнію та може вважатися ефективним підходом до модифікації напівпровідникових матеріалів, призначених для експлуатації в середовищах з високим радіаційним впливом.

Ключові слова: *напівпровідник, кремній, хром, легування, опромінення, протон, анігіляція позитронів*