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EFFECT OF DYSPROSIUM ATOMS INTRODUCED DURING THE GROWTH PHASE ON THE FORMATION OF RADIATION DEFECTS IN SILICON CRYSTALS

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In this study, the formation and reduction mechanisms of radiation defects resulting from the incorporation of dysprosium (Dy) atoms during the growth process of silicon crystals (FZ) were investigated. Deep-level defects formed after doping n-type silicon with dysprosium and irradiating it with ^{60}Co γ-rays were analyzed using Deep Level Transient Spectroscopy (DLTS). The research revealed that in the presence of dysprosium, the concentration of defects such as A-center (vacancy-oxygen complex) and E-center (vacancy-phosphorus complex) decreased significantly - by 2-4 times - compared to control samples. EDS spectral analysis was conducted to determine the concentration of surface element atoms in the sample, which demonstrated that the Dy element was uniformly distributed on the silicon surface and present in sufficient concentration. These results substantiate that Dy atoms in silicon play a passivating role, inhibiting the kinetics of radiation defect formation, consequently increasing the radiation resistance of silicon-based structures.

Keywords: *Dysprosium-doped silicon; Radiation defects; Gamma radiation; DLTS (Deep-Level Transient Spectroscopy); Neutron activation analysis; EDS (Energy Dispersive Spectroscopy); A-center; E-center; Crystal growth; Oxygen-vacancy complex; Radiation stability*

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INTRODUCTION

With the rapid advancement of modern electronics, particularly in the fields of micro- and nanoelectronics, there is a growing demand for materials with enhanced physicochemical, structural, and electrical properties. In this context, silicon (Si) holds a leading position as the most widely used primary semiconductor material. Silicon crystals are utilized to produce highly integrated circuits, high-speed photodiodes, radiation-resistant detectors, memory elements, as well as solar cells and numerous other electronic devices. One of the key factors determining the reliability and stability of such devices is the nature of internal and external defects in the material [1-3].

Defects that directly affect the performance of semiconductor materials, especially in silicon, are formed as a result of the interaction between vacancies (V) created by high-energy particles (such as γ-rays, protons, neutrons, and alpha particles), substitutional donors and acceptors (P, As, B), and oxygen atoms (O) present in the crystal lattice. Consequently, complex radiation defects with deep energy levels emerge. These defects lead to the recombination of electron-hole pairs and significantly impact the sensitivity, noise level, and operational lifespan of devices [4-5].

Modern scientific research is exploring numerous approaches to reduce the formation of radiation defects, decrease their stability, or neutralize them completely. One such approach is the method of doping silicon with rare earth elements (REE) [6-11]. This approach aims, in particular, to limit the activity of defects by gettering them, that is, removing them from the active parts of the crystal lattice and binding them in structural voids or peripheral regions. Due to their large ionic radius and chemical inertness, REE atoms do not actively bond with oxygen atoms or donor elements [7]. However, they strongly interact with existing defects, reducing their energetic activity. For example, scientific literature reports that it is possible to reduce the density of A- and E-centers formed in silicon by 2-4 times using elements such as Sm, Gd, Er, and Tm [12-14].

Among rare-earth elements, dysprosium (Dy) stands out with its unique physical properties. Primarily, Dy possesses a relatively large magnetic moment, which makes it a potential material for spintronic devices. Additionally, Dy atoms easily oxidize in the crystal lattice of silicon, forming oxide nanophases in the form of Dy_2O_3[2]. These phases bind oxygen atoms to themselves, preventing the formation of vacancy oxygen complexes. As a result, the crystalline structure of silicon becomes more stable, the occurrence of defects decreases, and its radiation resistance increases. However, the new defect states that arise during the Dy doping process and their kinetic behavior have not been thoroughly studied, necessitating further research in this direction [9].

The results of this study can be applied in the development of radiation-resistant electronic devices based on silicon, including optoelectronic detectors, photodiodes, and high-reliability integrated circuits [15-18]. Additionally, through in-depth analysis of the properties of defects arising from Dy doping, new possibilities for the application of rare-earth

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elements in silicon materials science are identified. This holds significant importance not only for fundamental science but also for applied device technologies.

MATERIALS AND METHODS

For the study, samples of ultra-pure n-type monocrystalline silicon were used. Their resistivity ranged from 10 to 65 Ω×cm, and the concentration of optically active interstitial oxygen atoms in the crystal lattice was in the range of (5×10^{16} - 7×10^{17}) cm^{-3}. The element dysprosium (Dy) was introduced into the silicon structure as a dopant during the growth process - at the stage of crystal growth from the solution. The samples were irradiated at room temperature (300 K) using γ-quanta emitted from the ^{60}Co isotope [16,19]. The radiation intensity was 3.1×10^{12} quanta/cm^2×s. For comparison, silicon samples (control samples) with the same oxygen content, but without dysprosium introduction, were irradiated under the same conditions.

Deep-level capacitance spectroscopy (DLTS) was used to detect radiation defects [8,10,21]. Schottky barriers were formed by evaporating gold (Au) onto the silicon surface under high vacuum conditions. Chemically deposited nickel (Ni) was used as the ohmic contact, and in some cases, antimony (Sb) or aluminum (Al) was additionally evaporated [20]. DLTS measurements were conducted in constant capacitance and constant voltage modes.

In addition, energy-dispersive X-ray spectroscopy (EDS) techniques were employed to evaluate the surface morphology and elemental composition of silicon samples doped with dysprosium [22,24,25].

RESULTS AND DISCUSSION

The energy characteristics of deep levels in silicon samples doped with dysprosium and in undoped control samples, both obtained by growth from solution, were determined using the DLTS method before and after each irradiation stage. The analysis revealed that the oxygen concentration differs significantly depending on the silicon composition: in oxygen-free silicon samples, the amount of optically active oxygen (N_O^{OA}) was approximately 5×10^{16} cm^{-3}, while in oxygen-containing crystals, this amount reached up to 7×10^{17} cm^{-3}. This is considered an important factor directly influencing the formation of radiation defects and the emergence of deep levels.

Fig. 1 (curve 2) shows a newly identified deep-level defect revealed by DLTS spectra of γ-irradiated n-Si<Dy> samples. This level exhibits an ionization energy of $E_c - 0.17$ eV and an electron capture cross-section of approximately $\sigma_n \approx 1\times10^{-14}$ cm^2. Based on the extracted parameters, this defect is attributed to the well-known A-center, corresponding to a vacancy–oxygen (V–O) complex [15,23].

As shown in Fig. 1 (curve 1), the presence of A-centers was observed in oxygen-containing n-Si control samples after gamma irradiation. Notably, the concentration of these centers in undoped silicon changes linearly with increasing radiation dose, while doped samples do not exhibit this characteristic. Additionally, comparative analysis revealed that the quantity of A-centers in the control samples is significantly higher compared to samples doped with dysprosium.

DLTS analysis of oxygen-free control silicon samples revealed the formation of an additional radiation defect - an E-center - in these samples under the influence of γ-radiation. The ionization energy of this defect is E_c-0.43 eV, and its electron capture cross-section is 1.8×10^{-15} cm^2. Interestingly, in silicon doped with dysprosium, a significant decrease in the concentration of E-centers was observed compared to the control samples - almost tenfold (Fig. 2, curves 1 and 2).

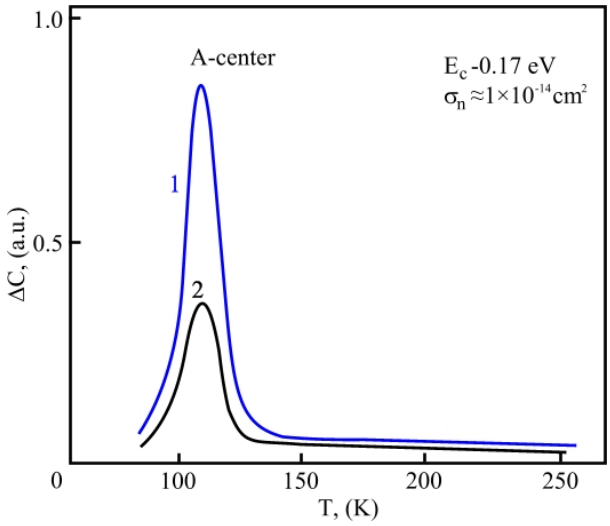

Figure 1. DLTS spectra of n-Si and n-Si<Dy> samples after γ-irradiation ($N_O^{OA}=7\times10^{17}$ cm^{-3}): 1 - control sample (n-Si); 2 - dysprosium-doped sample (n-Si<Dy>)

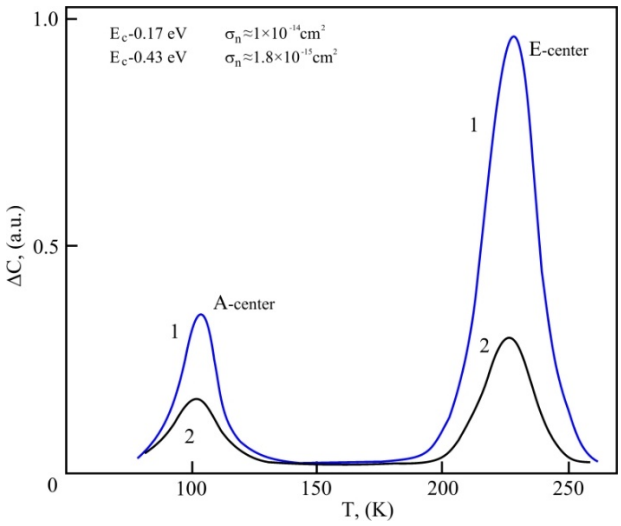

Figure 2. DLTS spectra of n-Si and n-Si<Dy> samples after γ-irradiation ($N_O^{OA}=7\times10^{17}$ cm^{-3}): 1 - control sample (n-Si); 2 - dysprosium-doped sample (n-Si<Dy>)

Based on the obtained samples, neutron activation analysis and EDS analysis were conducted to determine the concentration of Dy atoms on the surface and in the volume of the sample. The results of neutron activation analysis

indicate the presence of dysprosium atoms in the silicon sample at a high concentration - approximately $(3\times10^{16} – 4\times10^{18})$ cm^{-3}.

In Fig. 3, the concentration of elements on the surface of an oxygen-free silicon sample was studied using the energy-dispersive X-ray spectroscopy (EDS) method.

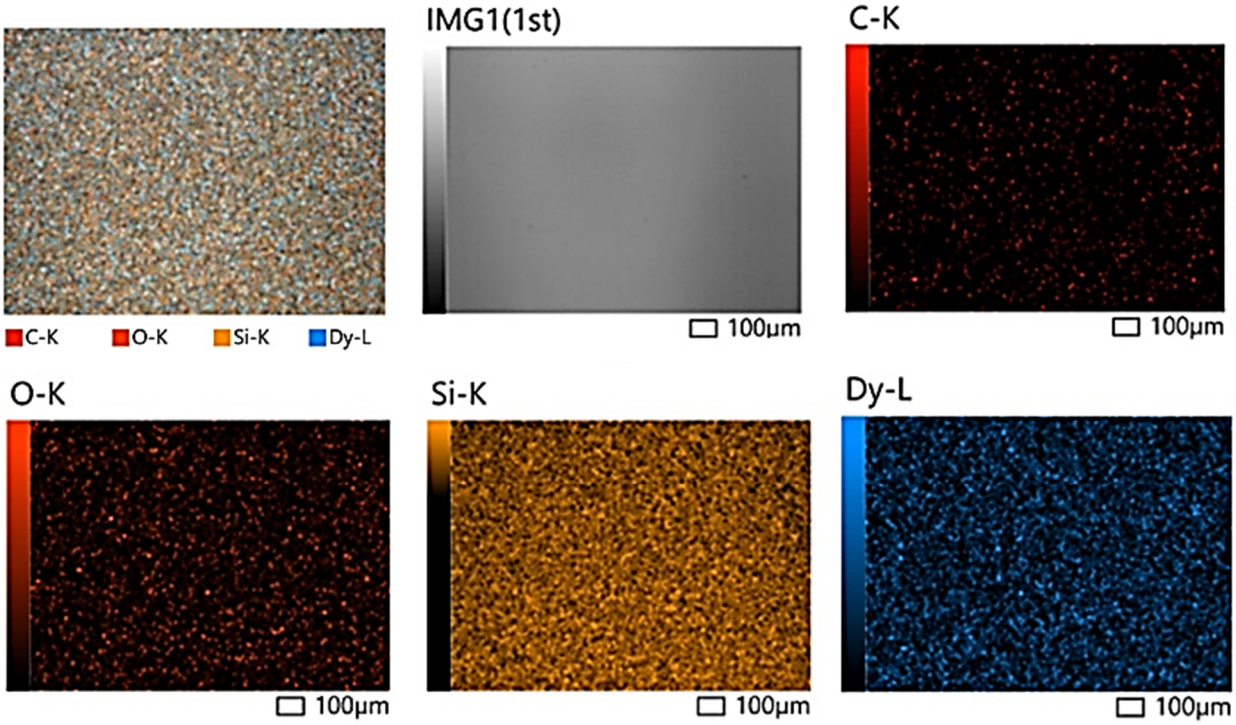

Figure 3. Image of the EDS spectral analysis for the n-Si sample.

Based on the analysis results, we can conclude that dysprosium atoms are evenly distributed on the surface of the silicon sample and in its adjacent regions. The mass fraction of dysprosium was found to be 0.16%, while its atomic fraction was 0.02%, which corresponds to the neutron activation analysis results (Table 1). These findings indicate the presence of Dy atoms both on the surface and within the volume of the silicon sample, demonstrating that their distribution is sufficiently homogeneous.

Table 1. Elemental composition of the surface of the n-Si<Dy> sample as determined by energy-dispersive X-ray spectroscopy (EDS).

Element	Line	Mass%	Atom%
C	K	10.27±0.10	21.09±0.20
O	K	0.37±0.01	0.57±0.02
Si	K	89.20±0.09	78.32±0.08
Dy	L	0.16±0.02	0.02±0.00
Total		100.00	100.00

CONCLUSIONS

In this work, a thorough analysis was conducted on the incorporation of dysprosium (Dy) as a dopant into ultra-pure n-type single-crystal silicon samples during the crystal growth stage (solution growth method) and its effect on radiation stability. The study utilized silicon samples with specific resistivity ranging from 10 to 65 Ω×cm and concentrations of optically active interstitial oxygen atoms between $(5\times10^{16} - 7\times10^{17})$ cm^{-3}.

Deep levels of samples exposed to gamma radiation (^{60}Co, 3.1×10^{12} quanta/cm^2×s) were studied using the DLTS method. The results showed that in silicon doped with Dy, after γ-radiation, A-centers with an ionization energy of E_c-0.17 eV were detected. These centers correspond to oxygen-vacancy (O-V) complexes. Additionally, the concentration of A-centers in silicon with Dy doping was significantly lower compared to the control samples, indicating a decreased formation rate of radiation defects.

In oxygen-free silicon, E-centers with an energy of E_c-0.43 eV were detected as a result of irradiation. The quantity of these centers was observed to be up to 10 times higher compared to samples doped with Dy. This clearly demonstrates the inhibitory effect of the Dy element on the mechanisms of defect formation.

EDS and neutron activation analyses confirmed the incorporation of the element dysprosium into the silicon structure. According to the EDS results, Dy atoms are uniformly distributed on the silicon surface with a mass fraction of 0.16% and an atomic fraction of 0.02%. Neutron activation analysis showed that the Dy concentration is in the range of $(3\times10^{16} - 4\times10^{18})$ cm^{-3}. Despite such high concentration, it was determined that Dy atoms are electrically passive and are positioned in the crystal lattice without forming deep energy levels.

In general, the conducted research indicates that doping silicon with a rare-earth element such as dysprosium during the growth stage from solution enhances its radiation stability and significantly reduces the probability of deep-level defect formation under the influence of γ-radiation.

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ВПЛИВ АТОМІВ ДИСПРОЗІЮ, ВВЕДЕНИХ НА ЕТАПІ ВИРОЩУВАННЯ, НА ФОРМУВАННЯ РАДІАЦІЙНИХ ДЕФЕКТІВ У КРИСТАЛАХ КРЕМНІЮ

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У цьому дослідженні проаналізовано механізми формування та зменшення радіаційних дефектів, що виникають у результаті впровадження атомів диспрозію (Dy) під час вирощування кристалів кремнію методом зонного плавлення (FZ). Глибокі рівні дефектів, що утворилися після легування n-типу кремнію диспрозієм і опромінення його γ-променями ізотопу ^{60}Co, були проаналізовані методом глибокорівневої ємнісної спектроскопії (DLTS). Встановлено, що у присутності диспрозію концентрація дефектів типу A-центр (вакансійно-кисневий комплекс) і E-центр (вакансійно-фосфорний комплекс) значно зменшується — у 2–4 рази у порівнянні з контрольними зразками. Спектральний аналіз методом EDS показав, що атоми Dy рівномірно розподілені по поверхні кремнію та присутні в достатній концентрації. Отримані результати підтверджують, що атоми Dy у кремнії відіграють пасивуючу роль, уповільнюючи кінетику формування радіаційних дефектів і підвищуючи радіаційну стійкість кремнієвих структур.

Ключові слова: *кремній, легований диспрозієм; радіаційні дефекти; гамма-випромінювання; DLTS (глибокорівнева ємнісна спектроскопія); нейтронно-активаційний аналіз; EDS (енергетично-дисперсійна рентгенівська спектроскопія); A-центр; E-центр; вирощування кристалів; киснево-вакансійний комплекс; радіаційна стійкість*