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Research Article

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EFFECT OF γ-IRRADIATION ON THE ELECTRICAL AND PHOTOELECTRIC PROPERTIES OF Cu-INTERCALATED GaSe SINGLE CRYSTALS

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The effects of γ-irradiation on the electrical and photoelectric properties of Cu-intercalated layered GaSe single crystals were systematically investigated. Cu intercalation was performed electrochemically for different durations, and the samples intercalated for 60 min, which exhibited the highest electrical conductivity, were selected for subsequent investigations. The electrical properties of Cu-intercalated GaSe single crystals were studied at absorbed γ-irradiation doses of 0, 1, 5, 10, and 15 kGy. Analysis of the temperature-dependent electrical conductivity revealed that the activation energy increased from 0.04 to 0.07 eV in the low-temperature region (100–250 K) and from 0.18 to 0.30 eV in the high-temperature region (250–300 K) with increasing irradiation dose. At the same time, the room-temperature electrical conductivity exhibited a non-monotonic dose dependence, increasing at 1 kGy and subsequently decreasing at higher doses. The spectral photocurrent was measured at 300 and 110 K under a constant bias voltage of 50 V. A decrease in photocurrent was observed after Cu intercalation and at 1 kGy, whereas a pronounced increase occurred at 15 kGy, reaching maximum values of 5.93×10^{-6} A at 300 K and 3.20×10^{-6} A at 110 K. These results demonstrate that Cu intercalation and γ-irradiation modify charge transport and photoelectric response in GaSe single crystals in a manner dependent on intercalation time, irradiation dose, and temperature.

Keywords: *p-GaSe single crystal; Cu intercalation; electrochemical intercalation; γ irradiation; electrical conductivity; photoconductivity*.

1. Introduction

Layered semiconductors of the $A^{III}B^{VI}$ semiconductors are characterized by the presence of strong covalent bonds within the crystal layers and weak van der Waals (vdW) interactions between the layers. This structural feature allows the introduction of various atoms and ions into the interlayer spaces, which, as a result, creates wide opportunities for controlling the electronic structure, charge transport processes and optical properties of the material [1, 2]. These structural characteristics make layered semiconductors promising for electronic, optoelectronic, and photodetection applications [1].

Among these materials, gallium selenide (GaSe) is one of the characteristic representatives of layered semiconductors of group $A^{III}B^{VI}$. In the GaSe crystal, the atomic layers formed in the sequence Se–Ga–Ga–Se are interconnected by weak vdW forces [1]. GaSe single crystals are distinguished by p-type conductivity, high optical and photoelectric

sensitivity, as well as the dependence of the mobility of charge carriers and the photoelectric response on the structural and defect states [3-6]. The observation of photoconductivity and photoluminescence phenomena in GaSe crystals of various compositions and modifications indicates that this material is a convenient system for studying the effect of external influences on charge transport and recombination processes [4, 6-8]. At the same time, the effect of electron irradiation on the electrical and capacitance-voltage characteristics of GaSe-based heterostructures has also been shown [9].

One of the important methods for controlling the functional properties of layered semiconductors is intercalation. During intercalation, the introduction of foreign atoms or ions into the interlayer vdW gaps can change the structural and electronic properties of the material without completely destroying the covalent bonds in the main crystal layers [2]. Depending on the nature, concentration and location of the intercalated component, the concentration of charge carriers, electronic energy levels, conductivity and optical response can change significantly [2, 10-13]. In particular, Cu intercalation has been shown to affect the electronic structure and electrical properties of various layered chalcogenides, and can even lead to semiconductor–metal transitions in certain systems [11-13]. Theoretical calculations for GaSe also show that modification with Cu can lead to changes in the energy band structure [14].

Modification of the optical and structural properties of Cu-intercalated GaSe crystals has also been observed in recent studies. In our previous work, the optical properties of Cu-intercalated GaSe single crystals were investigated and it was found that intercalation has a significant effect on the optical response of the material [15]. Later, the effect of γ-irradiation on the Raman, photoluminescence and UV–Vis absorption properties of Cu-intercalated GaSe crystals was studied [16]. These results indicate that Cu intercalation and γ-irradiation can interact with phonon, electron and recombination processes in GaSe crystals. However, the behavior of such modifications in terms of direct electrical conductivity and photoelectric response needs to be investigated separately.

On the other hand, ionizing γ-irradiation can affect the electrical and photoelectric parameters of semiconductors by causing changes in structural defects, trap levels, and charge carrier capture–release processes. The effect of γ-irradiation on the photoelectric and dielectric properties of GaSe-based materials has been previously studied in various modified systems [17–19]. For example, the effect of γ-irradiation on the photoelectric properties of Sb–GaSe structures has been studied [17], and changes in dielectric parameters and conductivity have been observed in Tl-doped GaSe single crystals with increasing γ-irradiation dose [18]. In addition, the effect of γ-irradiation on photoconductivity has also been shown in

$(GaSe)_{0.8}(InSe)_{0.2}$ single crystals [19]. These results indicate that γ-irradiation can play an important role in modifying charge transport and photoelectric processes in GaSe-based materials.

However, most of the existing studies are devoted either to the effect of γ-irradiation on primary/doped GaSe crystals or to the consequences of intercalation in various layered materials [2, 11–13, 17–19]. To the best of our knowledge, the combined effects of Cu intercalation and subsequent γ-irradiation on the electrical conductivity and spectral photocurrent response of bulk GaSe single crystals have not been systematically investigated. In particular, the response of the interlayer medium, previously modified by Cu intercalation, to subsequent γ-irradiation and the combined effect of these two external effects on charge transport processes are of particular scientific interest. In this regard, determining the changes in the electrical and photoelectric parameters of Cu-intercalated GaSe as a function of irradiation dose is important for understanding its dose-dependent response to ionizing radiation.

In the works [20-24], the authors provided a comprehensive physical and chemical analysis of the optical, Raman, and other spectra of Ga-based semiconductor-filled composite materials in their initial state and after irradiation with gamma quanta. It was shown that, compared with the pristine material, the Ga-based semiconductor-filled composite material exhibits radiation resistance after a certain dose [20-24].

In addition, the works [25-29] extensively investigated the effects of radiation and changes in concentration on the electrical and dielectric properties of semiconductors belonging to the $A^{III}B^{VI}$ group. Furthermore, the optical and electrophysical properties of Tl-based semiconductor materials containing two or more elements, as well as the effects of gamma radiation on these properties, have been studied [30-34]. In these works, the hypothesis was put forward that changes in concentration and the effect of gamma irradiation lead to an increase in disorder in crystalline materials and the formation of radiation-induced defects [25-34].

The aim of this work is to systematically investigate the effect of γ-irradiation on the electrical and photoelectric properties of Cu-intercalated p-type GaSe single crystals. For this purpose, the electrical properties of GaSe–Cu samples prepared at different intercalation times were compared, selected samples were exposed to 1 and 15 kGy absorbed γ-irradiation doses, and their electrical conductivity, as well as the spectral distribution of the photocurrent, were studied at different temperatures (300 and 110 K). Thus, in this work, the initial modifying effect of Cu intercalation was compared with the subsequent effect of γ-irradiation, and the

possibility of controlling charge transport and photoelectric processes in layered GaSe crystals by external influences was evaluated.

2. Materials and methods

In the research work, the electrical and photoelectric properties of GaSe single crystals intercalated with Cu and exposed to γ-irradiation at different doses were comprehensively investigated. The characteristic geometric dimensions of the studied samples were (5×2×0.5) mm^3. GaSe single crystals were obtained by the vertical Bridgman–Stockbarger method under high temperature gradient conditions. High purity Ga (99.999%) and Se (99.99999%) elements were used in the synthesis of the crystals. The components taken in stoichiometric proportions were placed in a pre-cleaned quartz ampoule, and in order to prevent oxidation, the ampoule was vacuumed to a pressure of 10^{-5} mm of mercury column and hermetically sealed. The homogenization of the components was carried out at a temperature of 873 K for 10–20 hours, and crystallization was carried out by controlled low-speed movement of the ampoule inside the oven.

The obtained crystals have a layered structure, with weak van der Waals interactions between the layers. Based on the X-ray diffraction results, the synthesized samples were attributed to the β-GaSe phase with a hexagonal structure. The parameters of the crystal lattice were a=3.755 Å and c=15.94 Å. The initial crystals had p-type conductivity, and their specific resistance at room temperature was (10^2-10^4) **(**Ω·cm). The structural and optical properties of GaSe single crystals before and after intercalation were studied in detail in our previous work [15-16].

The modification of GaSe single crystals with Cu was carried out by electrochemical intercalation. The presence of interlayer van der Waals spaces in the layered GaSe structure creates favorable conditions for the entry of foreign atoms, molecules and ions into the crystal structure. A 4% aqueous $CuSO_4$ solution was used as the electrolyte for Cu intercalation. In the electrochemical system, a stainless steel anode was connected, and a GaSe single crystal was connected as the cathode. The distance between the electrodes was 2.5 cm, and a constant voltage (U=1 V) was applied to the system. The intercalation process was carried out at a temperature of 70 °C for 60 minutes.

During the electrochemical process, the Cu ions in the electrolyte were introduced into the GaSe crystal under the influence of an electric field. After intercalation, the samples were prepared for subsequent γ-irradiation and electrical-photoelectric measurements. The effect of

Cu intercalation on the structural and optical properties of the GaSe crystal, including Raman, photoluminescence and UV–Vis spectroscopic results, was presented in detail in our previous work [16]. Therefore, these results are not repeated in the new article and are used only with appropriate references during the physical interpretation of the newly obtained electrical and photoelectric results.

Cu-intercalated GaSe single crystals were exposed to γ-irradiation in a MRX γ-25 device with a ^{60}Co radioisotope source. Irradiation was carried out at room temperature in high vacuum conditions. The dose rate of γ-irradiation was 117606 rad·s^{-1}. In the study, samples were irradiated to absorbed doses of 1 and 15 kGy. According to the given dose rate, the irradiation time for obtaining a 1 kGy dose was approximately 850 s (14 min 10 s), and for a 15 kGy dose it was 12755 s (3 h 32 min 35 s). Thus, different absorbed doses were obtained by changing the irradiation time in the same irradiation environment. After irradiation, the samples were prepared for electrical and photoelectric measurements and their characterization was carried out on the same day.

To study the electrical properties of Cu-intercalated and γ-irradiated GaSe single crystals, conductive ohmic contacts were created on the surface of the samples using silver paste. The contact pair was aligned along the crystallographic c-axis, so that the electrical current was measured in the *c*-axis direction. The distance between the contacts was (L = 0.5) mm. In order to investigate the current conduction mechanism and the temperature-dependent behavior of charge carriers in the samples, the current-voltage (*I–V*) characteristics were studied over a wide temperature range of 100–300 K.

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Electrophysical measurements were carried out in a specially designed metal cryostat under high vacuum conditions, where the pressure could be reduced to 10^{-3} Pa. The sample was cooled using liquid nitrogen, and the temperature was regulated using an electric heater, and the temperature was controlled by a thermocouple.

The *I–V* characteristics were measured by varying the applied voltage and recording the resulting current. The measurement system consisted of a TEC-9 constant voltage source, the sample under study, a resistance connected in series with the sample, and electrical measuring

devices for measuring the current intensity with voltage drop. The voltage drop across the sample was recorded with a B7-27A voltmeter. For high-sensitivity measurement of weak current intensities 10^{-15}-10^{-8} A, a B7-30 universal voltmeter-electrometer was used, and for measurement of relatively large current intensities 10^{-9}-10^{-3} A, a F-136 microvolt-nanoammeter was used.

The specific electrical conductivity of the samples was calculated using the measured current and voltage values

$$\sigma = \frac{I\,L}{S\,U}$$

where I is the electric current through the sample, L is the distance between the contacts, S is the cross-sectional area of the sample, and U is the voltage drop between the contacts.

Based on the analysis of the temperature-dependent electrical conductivity, the thermal activation processes of charge carriers were investigated and the activation energy was determined using the following Arrhenius-type expression:

$$\sigma = \sigma_0 \exp\left(-\frac{E_a}{k_B T}\right)$$

where, σ_0 is the temperature-independent coefficient, E_a is the activation energy, k_B is the Boltzmann constant, and T is the absolute temperature.

The photoelectric properties of the samples and the spectral distribution of the photocurrent were studied using an SF-4 spectrophotometer with a working spectral range of 200–2000 nm. Monochromatic illumination was provided by a 20 W incandescent lamp integrated into the optical system of the device. A monochromatic light flux corresponding to a certain wavelength was directed through the quartz optical window of the cryostat onto the sample surface and the photocurrent generated as a result of illumination was recorded.

Before measuring the photocurrent, the dark current (I_d) of the sample at a given constant voltage was determined, and then the full current (I_i) was measured under illumination at the same voltage. The additional photocurrent component generated as a result of illumination was determined by the expression

$$I_{fc} = I_i - I_d$$

Before measurements, the spectral intensity of the monochromatic illumination was calibrated in the wavelength range under study. This approach allowed minimizing the

influence of wavelength-dependent light intensity changes of the optical system on the measured photocurrent spectrum and comparatively evaluating the photoelectric response of the samples at different wavelengths.

The spectral distribution of the photocurrent was measured at room temperature (T=300 K) and at low temperature (T=110 K), applying a constant voltage (U=50 V) to the sample. A bias voltage of 50 V was selected to obtain a measurable photocurrent while maintaining stable operation of the samples. Measurements at low temperatures were carried out in a vacuum cryostat, which provided cooling of the sample with liquid nitrogen. The quartz optical window of the cryostat allowed monochromatic radiation to be delivered to the sample surface.

Thus, the response of GaSe single crystals to γ-irradiation after Cu intercalation, changes in charge transport processes, and the dependence of the photoelectric response on both γ-dose and temperature were comparatively determined through electrical and photoelectric measurements conducted under the same experimental conditions.

3. RESULTS AND DISCUSSION

3.1. Effect of Cu intercalation on the electrical properties of GaSe single crystals

To evaluate the effect of different intercalation times on the electrical properties of GaSe single crystals, the current-voltage characteristics of the samples were first compared. Figure 1 presents the lg$I$−lg$U$ dependences for the initial GaSe at a temperature of T=300 K and the samples intercalated with Cu for 15 min, 30 min, 1 h and 2 h. Here, I is the current intensity passing through the sample, and U is the applied voltage.

As can be seen from Figure 1, intercalation with Cu causes a significant change in the current–voltage characteristic of the GaSe single crystal. The current value differs between the curves obtained for different intercalation times, and a higher current is observed in the 1-hour intercalated sample. However, a monotonic increase in the current is not observed with increasing intercalation time; the current decreases in the 2-hour sample compared to the 1-hour sample.

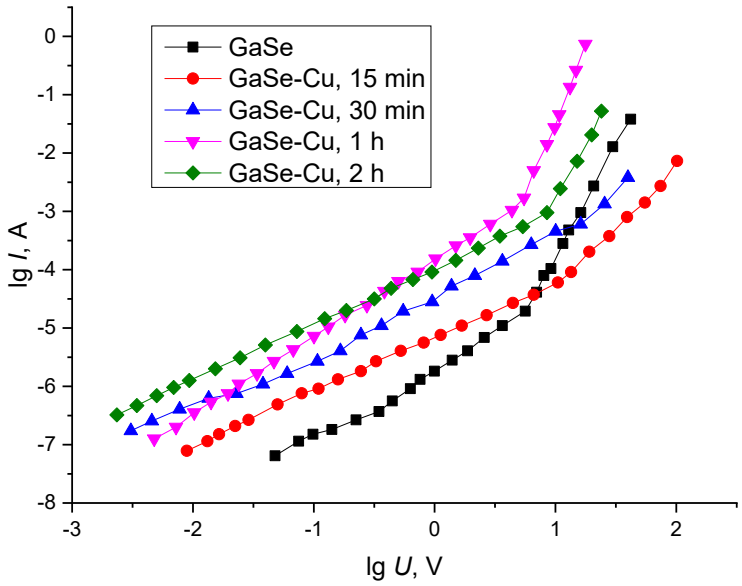


Fig. 1. Logarithmic current–voltage characteristics of pure GaSe and Cu-intercalated GaSe crystals at $T = 300$ K for different intercalation times (15 min, 30 min, 1 h, and 2 h).

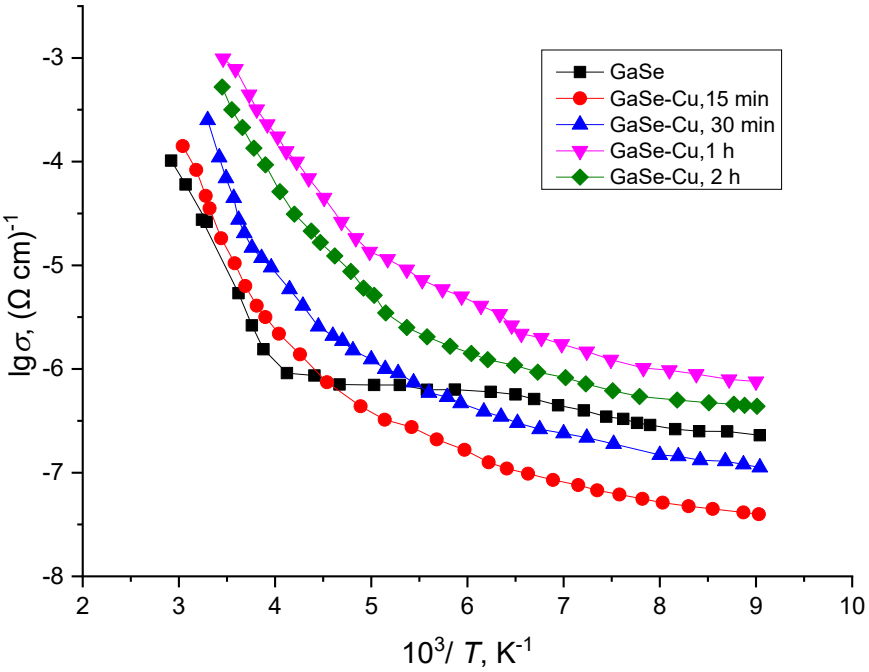


Fig. 2. Temperature dependence of the electrical conductivity of pure GaSe and GaSe crystals intercalated with Cu at different intercalation times (15 min, 30 min, 1 h and 2 h) in the temperature range T=110–300 K

The temperature dependence of the electrical conductivity is shown in Figure 2. The increase in conductivity with increasing temperature in the studied samples indicates a semiconducting temperature dependence. After Cu intercalation, a change in the absolute value of the conductivity is observed.

Table 1. Activation energies and electrical conductivity at room temperature for pure GaSe and Cu-intercalated samples with different intercalation periods, determined in the low-temperature region (110–250 K, E_{a1}) and high-temperature region (250–300 K, E_{a2}).

Sample	E_{a1} (eV)	E_{a2} (eV)	σ, $(\Omega\cdot cm)^{-1}$
GaSe	0.003	0.36	1×10^{-4}
GaSe-Cu (15 min)	0.12	0.1	1.4×10^{-4}
GaSe-Cu(30 min)	0.07	0.09	2.5×10^{-4}
GaSe-Cu (1 h)	0.05	0.08	8×10^{-4}
GaSe-Cu (2 h)	0.06	0.07	5×10^{-4}

As can be seen from Table 1, while the electrical conductivity at T=300 K for pure GaSe is 1×10^{-4} $(\Omega\cdot cm)^{-1}$, this value for the samples intercalated with Cu is 1.4×10^{-4}, 2.5×10^{-4}, 8×10^{-4} and 5×10^{-4} $(\Omega\cdot cm)^{-1}$ for 15 minutes, 30 minutes, 1 hour and 2 hours, respectively.

Thus, the maximum value of the electrical conductivity is achieved during 1 hour of intercalation. At a longer, 2 hours intercalation period, a decrease in the conductivity from 8×10^{-4} to 5×10^{-4} $(\Omega\cdot cm)^{-1}$ is observed. This result indicates that increasing the intercalation time does not lead to a linear increase in the electrical conductivity.

During the quantitative analysis of the temperature dependence, two different temperature regions were considered in the temperature dependence of the conductivity and the corresponding activation energies E_{a1} (100–250 K) and E_{a2} (250–300 K) were determined. E_a was obtained from the slope of linear fits of $\ln\sigma$ versus $1000/T$. The obtained values are presented in Table 1. After Cu intercalation, a change in the activation energy is observed in both temperature regions, which indicates that the temperature-dependent electrical transport has changed compared to the original GaSe.

3.2. Effect of γ-irradiation on the electrical properties of Cu-intercalated GaSe single crystals

As we have established in 3.1, 1 hour Cu intercalation provided a sample characterized by higher electrical conductivity. Therefore, GaSe single crystals intercalated with Cu for 1 hour were chosen as the main sample in the further study of the effect of γ-irradiation. The samples were irradiated at absorbed γ-doses of 1, 5, 10 and 15 kGy and the effect of irradiation on the electrical transport properties was investigated based on the current–voltage characteristics and temperature-dependent electrical conductivity.

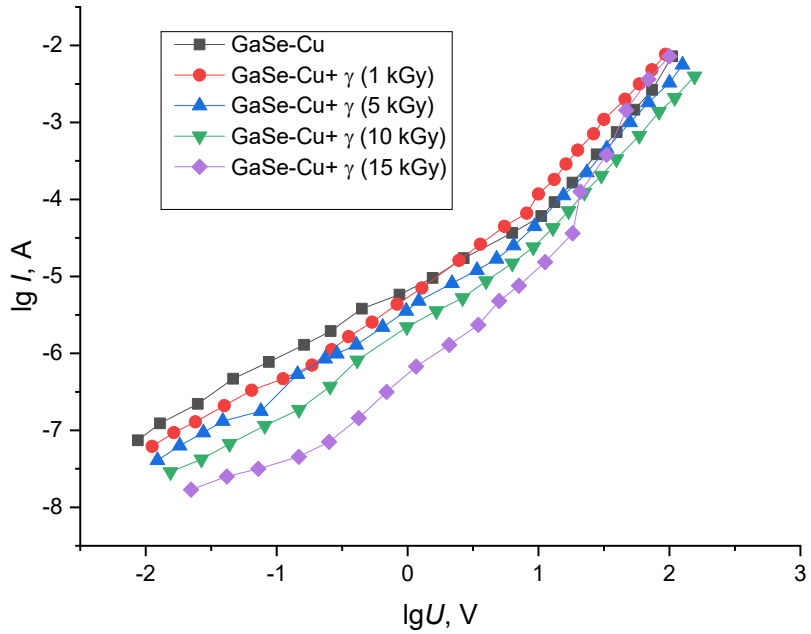


Fig. 3. Logarithmic current–voltage characteristics of GaSe crystals irradiated with γ-quanta at different doses (D = 0;1;5;10;15 kGy) and intercalated with Cu at a temperature of T = 300 K and a time of t =1 hour

Figure 3 shows the lg$I$-lg$U$ characteristics of Cu-intercalated GaSe samples irradiated at different γ-doses at T = 300 K. As can be seen from the figure, γ-irradiation causes noticeable changes in the current-voltage characteristics of the samples. With increasing irradiation dose, the current value does not change in the same direction over the entire voltage interval. Especially at low doses, at D=1 kGy, a decrease in the current is observed compared to the initial sample. At higher doses, the change in the current-voltage characteristic is enhanced.

This result indicates that γ-irradiation affects the charge transport process in Cu-intercalated GaSe. However, it is not possible to determine the specific microscopic cause of

the change based on *I-V* characteristics alone. Therefore, for a more detailed assessment of the γ-dose effect, the temperature dependence of the electrical conductivity was investigated.

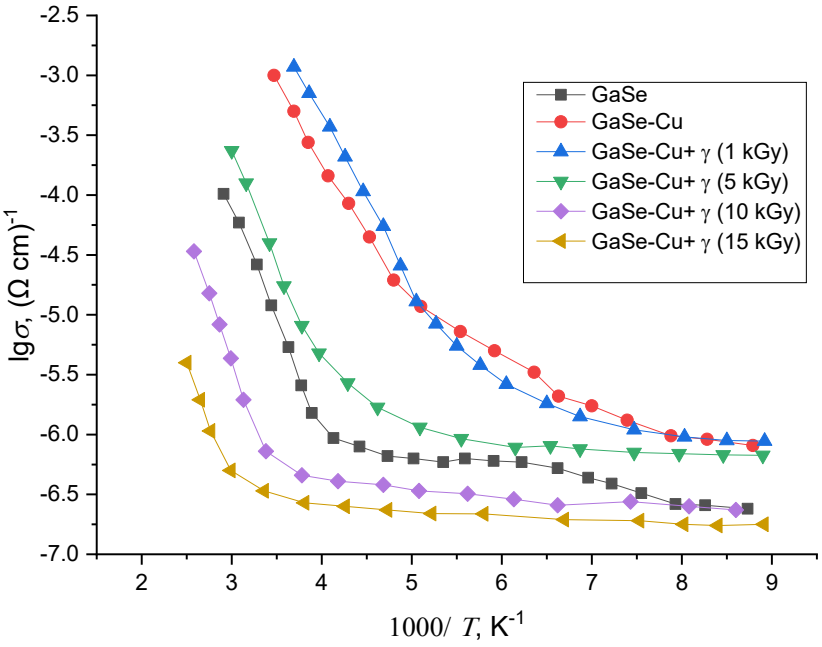


Fig. 4. Logarithmic current–voltage characteristics of Cu-intercalated GaSe single crystals irradiated at doses of 0, 1, 5, 10, and 15 kGy, measured at $T = 300$ K.

Figure 4 presents the temperature dependence of the electrical conductivity of GaSe, GaSe-Cu and GaSe-Cu samples irradiated with γ-rays at doses of 1, 5, 10 and 15 kGy in the temperature range 110-300 K.

In all samples, an increase in electrical conductivity is observed with increasing temperature. This behavior is consistent with the existence of a temperature-activated charge transport process. At the same time, increasing the γ-dose affects both the value of the conductivity and the nature of its temperature dependence.

Here, as in the previous table, two temperature regions should be separately highlighted: 100-250 K and 250-300 K. This is due to the fact that the activation energies are determined precisely for these two temperature ranges.

The activation energies determined as a result of the quantitative analysis of the temperature-dependent electrical conductivity and the values of the electrical conductivity at T=300 K are summarized in Table 2.

Table 2. Activation energies and electrical conductivity at room temperature in the low (E_{a1}) and high (E_{a2}) temperature regions of a Cu-intercalated GaSe sample for different γ-irradiation doses.

Dose (kGy)	E_{a1} (eV)	E_{a2} (eV)	σ $(\Omega \cdot cm)^{-1}$
0	0.18	0.04	5×10^{-4}
1	0.19	0.04	1×10^{-3}
5	0.20	0.05	6.3×10^{-4}
10	0.24	0.06	2.5×10^{-4}
15	0.30	0.07	1.6×10^{-5}

Thus, γ-irradiation affects the electrical transport properties of Cu-intercalated GaSe single crystals in a dose-dependent manner. The initial changes observed at low doses of γ-rays are accompanied by more noticeable changes in the electrical conductivity and temperature-dependent parameters at higher doses. The change in activation energies indicates that γ-irradiation affects the energetic nature of charge transport processes in the crystal. However, in order to determine how the observed electrical changes are reflected in the photoelectric properties, the spectral distribution of the photocurrent was studied at different temperatures and irradiation conditions with γ-rays.

3.3. Effect of γ-irradiation on the photoelectric properties of Cu-intercalated GaSe

In order to determine how the changes in electrical properties caused by γ-irradiation are reflected in the photoelectric properties, the spectral distribution of the photocurrent of Cu-intercalated GaSe single crinystals was studied at different temperatures and radiation doses. The measurements were carried out at temperatures T=300 K and T=110 K at a constant voltage U=50 V.

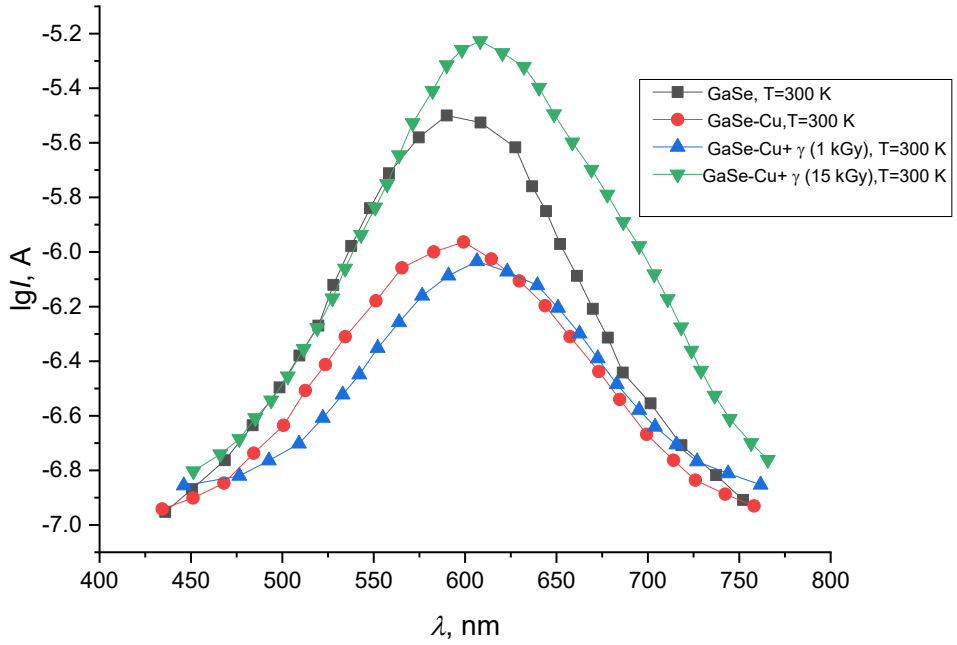


Fig. 5. Spectral distribution of photocurrent (I) for GaSe, GaSe-Cu (Cu-intercalated), and γ-irradiated single crystals at absorbed doses of 1 kGy and 15 kGy, measured at $T = 300$ K under a constant applied bias of $U = 50$ V.

Figure 5 presents the temperature dependence of the electrical conductivity of pristine GaSe, Cu-intercalated GaSe, and Cu-intercalated GaSe irradiated at doses of 1, 5, 10, and 15 kGy. In all samples, the photocurrent is observed mainly in the visible spectral region, and the spectra are similar in terms of general shape. At the same time, Cu intercalation and subsequent γ-irradiation cause changes in the intensity of the photocurrent and the position of the spectral maximum.

While the maximum photocurrent in a pure GaSe single crystal is $3.16 \cdot 10^{-6}$ A, after Cu intercalation this value decreases to $1.09 \cdot 10^{-6}$ A. Thus, Cu intercalation is accompanied by a decrease in the maximum photocurrent by about 65%. This result indicates that Cu intercalation has a significant effect on the photoelectric properties of the GaSe single crystal.

The effect of γ-irradiation is characterized by a non-monotonic change in the photocurrent. Thus, at an absorbed dose of 1 kGy, the maximum photocurrent decreases to $9.25 \cdot 10^{-7}$ A. When the radiation dose is increased to 15 kGy, the photocurrent increases sharply and reaches a value of $5.93 \cdot 10^{-6}$ A. Thus, at a dose of 15 kGy, the maximum photocurrent is higher than both the initial GaSe–Cu sample and the pure GaSe sample. These results

demonstrate that γ-irradiation has a dose-dependent, non-monotonic effect on the photoelectric parameters.

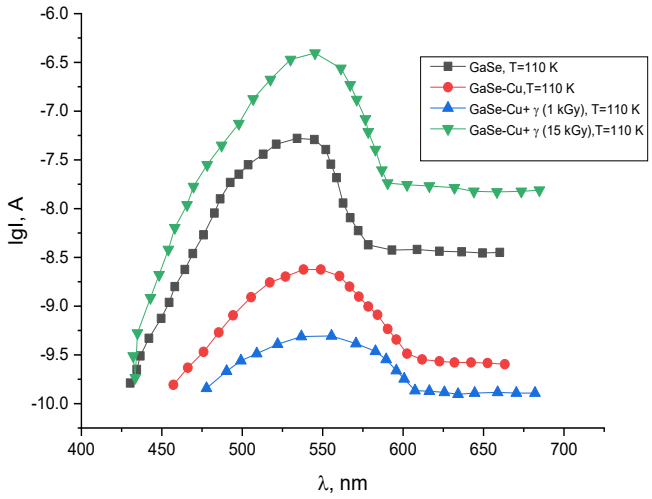


Fig. 6. Spectral distribution of photocurrent for GaSe, Cu-intercalated GaSe (GaSe-Cu), and γ-irradiated (with 1 kGy and 15 kGy absorbed doses) single crystals, measured at a temperature of T = 110 K under a constant applied bias of U = 50 V.

Figure 6 presents the spectral distribution of the photocurrent of pure GaSe, GaSe–Cu, and GaSe–Cu samples irradiated with 1 and 15 kGy γ-rays at a temperature of T = 110 K. Reducing the temperature from 300 K to 110 K is accompanied by a decrease in the absolute value of the photocurrent in all samples. Reducing the temperature from 300 K to 110 K decreases the photocurrent intensity in all samples, while the spectral maximum exhibits sample-dependent shifts in wavelength.

At a temperature of 110 K, the maximum photocurrent for pure GaSe is $4.17 \cdot 10^{-7}$ A, and for GaSe–Cu it is $3.11 \cdot 10^{-7}$ A. Thus, the decrease in photocurrent after Cu intercalation is maintained even at low temperatures. After irradiation with 1 kGy of γ-rays, the maximum photocurrent decreases to $3.0 \cdot 10^{-7}$ A. In contrast, at a dose of 15 kGy, the photocurrent increases sharply, reaching a value of $3.20 \cdot 10^{-6}$ A.

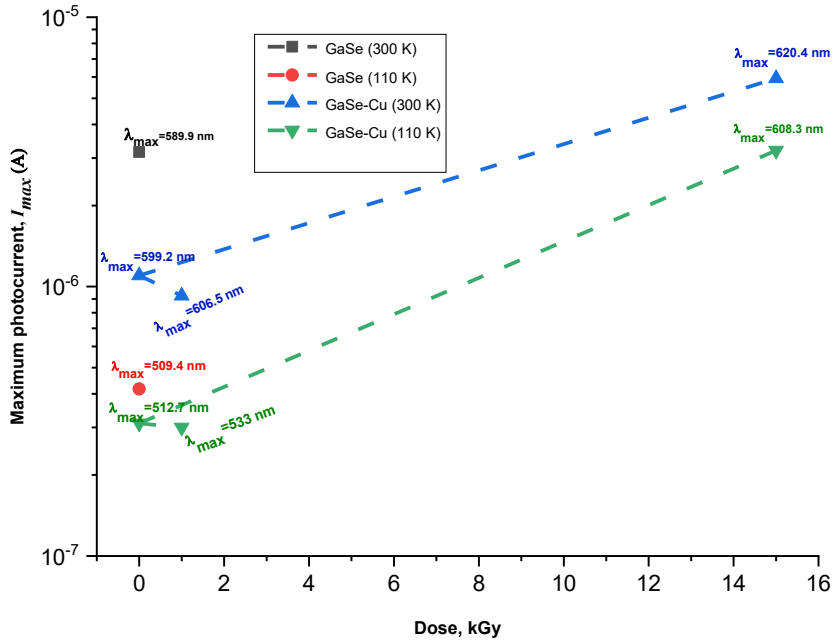


Fig. 7. Dependence of the maximum photocurrent on the γ-irradiation dose for pristine GaSe and Cu-intercalated GaSe single crystals measured at $T = 300$ K and $T = 110$ K.

Figure 7 shows the dependence of the maximum photocurrent on the absorbed dose of γ-radiation for temperatures T=300 K and T=110 K. The obtained results show that the photocurrent at both temperatures changes with the dose in the same way: at a dose of 1 kGy the photocurrent decreases, and at a dose of 15 kGy it increases significantly. At the same time, a decrease in temperature leads to a decrease in the absolute value of the photocurrent. Thus, both temperature and γ-radiation dose play an important role in the formation of the photoelectric response.

The obtained results, together with the structural and optical changes determined in previous studies, indicate that Cu intercalation and γ-irradiation interact to affect the photoelectric properties of GaSe single crystals [16]. However, it is not possible to unambiguously determine the specific microscopic mechanism of the observed changes based on the current photocurrent measurements. Therefore, the decrease in photocurrent at 1 kGy and the sharp increase at 15 kGy are considered experimental results indicating that the γ-dose has a different effect on the photoelectric response. Overall, the results show that Cu intercalation reduces the photocurrent of GaSe, while the effect of γ-irradiation causes a significant change in the photocurrent depending on the dose and temperature. In particular, the high photocurrent values observed at both 300 K and 110 K at a dose of 15 kGy indicate

that the response of Cu-intercalated GaSe to γ-irradiation is non-monotonic with increasing dose.

4. CONCLUSION

Cu intercalation changed the electrical and photoelectric properties of GaSe single crystals depending on the intercalation time, and the maximum value of electrical conductivity was observed at 60 minutes of intercalation. With an increase in the γ-irradiation dose, an increase in the activation energy E_{a1} increased from 0.18 to 0.30 eV and a decrease in electrical conductivity were determined in Cu-intercalated samples. The increase in E_a with increasing dose indicates a progressive modification of the thermally activated transport process, while the room-temperature conductivity exhibits a non-monotonic dose dependence. In photoelectric measurements, a decrease in the photocurrent was observed after Cu intercalation, an additional weakening at 1 kGy, and a sharp increase at 15 kGy. This dose dependence was maintained at both 300 K and 110 K, and a decrease in temperature led to a decrease in the absolute value of the photocurrent. Thus, it was determined that γ-irradiation has a different effect on the dark electrical conductivity and the photocurrent under illumination conditions. Overall, the obtained results indicate that Cu intercalation and γ-irradiation are important factors controlling the charge transport and photoelectric properties of GaSe.

Declarations

Competing Interests

The authors declare that they have no competing financial or non-financial interests, directly or indirectly related to the submitted work, during the past three years or any earlier period that could reasonably be perceived as influencing the work.

Availability of Data and Materials

The data and materials used in this study are available from the corresponding author upon reasonable request.

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