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Obtaining Ge–GeS:Nd Heterojunction and Research of Current–Voltage Curve

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For the first time, we grew an *n*-Ge–*p*-GeS:Nd heterojunction by the method of vacuum thermal evaporation, and we studied the possibility of rectifying the current by this heterojunction according to its current–voltage curve. In order to study the effect of radiation on the current–voltage curve of the heterojunction, samples were studied as subjected to different doses of gamma irradiation (of 50 and 150 krad). Moreover, the data obtained were compared and analyzed.

Вперше ми виростили гетероперехід *n*-Ge–*p*-GeS:Nd методою термовакуумного випаровування та вивчили можливість випрямлення струму цим гетеропереходом відповідно до його кривої струм–напруга. З метою вивчення впливу випромінення на криву струм–напруга гетеропереходу було досліджено зразки, що зазнавали різних доз гамма-опромінення (у 50 і 150 крад). Більше того, одержані дані було порівняно й проаналізовано.

Key words: heterojunction, vacuum thermal evaporation, current–voltage curve, dark current, gamma irradiation, generation and recombination processes.

Ключові слова: гетероперехід, термовакуумне випаровування, крива струм–напруга, темновий струм, гамма-опромінення, процеси ґенерації та рекомбінації.

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1. INTRODUCTION

Interest in GeS single crystals classifying as axialite increased after it became possible to reproduce a holographic recording on its surface. Over the past ten years, the greatest interest in layered GeS single crystals has arisen after scientists at the University of North Carolina of the United States of America obtained a nanostructure similar to cloves and made field effect transistors operating in the high-frequency band [1]. As a result, nanostructured lithium ions Li^+, which have the property of intercalation, are used in the manufacture of super capacitors of greater electric capacity and solar converters. The studies showed that being a direct-gap semiconductor, a layered GeS single crystal is also a photosensitive semiconductor-compound in the near-infrared and visible regions [2].

One of the main challenges facing modern electronics is the manufacture of radiation-resistant, environmentally friendly and cost-effective solar converters [3]. For this purpose, systems with different structures are developed and manufactured, namely, thin films, Schottky barriers, homo- and heterostructures, which are widely used in various fields of science and technology [4]. Among the noted structures, heterojunctions are distinguished by a high efficiency and a wider field of practical application [5].

2. METHODS OF OBTAINING

Despite the numerous advantages, for obtaining heterojunctions with high efficiency factor working in a stable operating mode, it is important to observe strictly the following conditions:

contacting semiconducting substances should have the same crystal structure;

parameters of crystal lattices should be as close as possible;

in both semiconducting substances, electronic transitions must be either direct or indirect.

In reality, you can find semiconductor elements and compounds satisfying all these conditions. If these conditions are not satisfied, an additional potential difference arises at the contact of the materials and the band structure is destroyed. To eliminate these drawbacks, it is necessary to use solid solutions consisting of several isomorphic components. The difference in the physical properties and geometrical sizes of atoms mutually replacing each other leads to deformation of the crystal lattice. It is possible to prevent deformation by changing the percentage of the elements making up the solid solution and converging the parameters of the crystal lattices of the substances in contact.

When changing the type of conductivity of the Ge crystal, phosphorus was used as an admixture. Phosphorus atoms, changing the type of conductivity and lattice parameters of the Ge crystal, do not allow the appearance of an additional potential difference at the contact of the Ge–GeS:Nd heterojunction.

The thermal spraying method was used for obtaining the Ge–GeS:Nd heterojunction. A $Ge_{1-x}Nd_xS$ polycrystal was placed on a Ge phosphor-doped substrate, which was located at a distance of 10–15 cm from the quartz vessel. The crystal was heated using a resistively controlled tungsten wire wound on a quartz vessel. When the temperature of the vessel reaches 350°C, because of sublimation, the polycrystal evaporates and absorbs into the germanium substrate [6]. The thickness of the absorbed layer is controlled by the time of sublimation. The temperature of the polycrystal was measured using a potentiometer KSP-4, which is included in the package of the vacuum post 'VUP-5M', the absorption process was carried out under a pressure of 10–6 mm Hg. The stoichiometric composition of the $Ge_{1-x}Nd_xS$ solid solution, the crystal structure, and lattice parameters close to the phosphor-doped Ge single crystal were determined using Vegard's law. In this case, to obtain a heterojunction with a minimum voltage, using a $Ge_{1-x}Nd_xS$ polycrystal on a Ge substrate, a solid solution of the composition $Ge_{0.98}Nd_{0.02}S$ was used. The quality of the resulting heterojunction is determined directly by its current–voltage characteristic and the alternating-current rectification ability.

3. EXPERIMENTAL DATA AND THEIR DISCUSSION

To determine the mechanism of generation and recombination of the electrical conductivity of the studied structure under the influence of various doses of gamma radiation, the current–voltage curve (VAC) curves in the forward and reverse directions of the structure was studied. As can be seen from Fig. 1, the VAC of the anisotropic

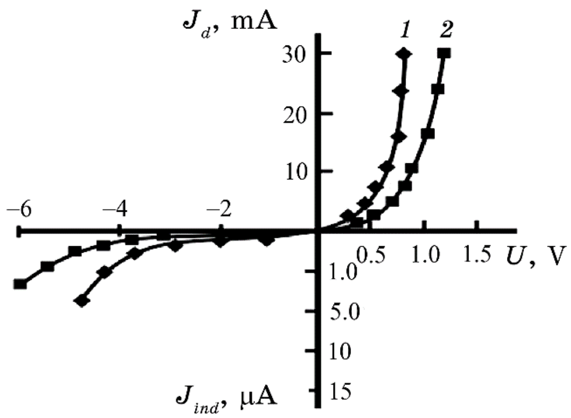

Fig. 1. Dark current–voltage curve of heterojunction Ge–GeS:Nd. *1*—300 K; *2*—100 K.

n-Ge–p-GeS:Nd heterojunction is asymmetric. This is evidence of the existence of a potential difference at the junction of Ge and GeS:Nd semiconductors and the dependence of the current strength in the circuit on its direction. The dark current strength at a reverse voltage value $U = 1$ V is of 0.1–0.5 μA. And the current strength is of 40–50 mA at the same forward voltage. When the reverse voltage $U > 4$–5 V is observed, the process of 'breakdown' in the p–n-junction is observed.

A change in temperature in the range of 100–300 K leads to an increase in the reverse dark current and a shift of the characteristic to the low-voltage region. These patterns are explained by a decrease of the forbidden bandwidth of the semiconductor material.

The study of the VAC characteristics of the Ge–GeS:Nd heterojunction shows that the dependence of the forward and reverse currents on the voltage of the external electric field obeys the law

$$I = I_0\left[\exp\left(qU / (nkT)\right) - 1\right].$$

Here, I_0 is saturation current strength; q—electronic charge; U—voltage; k—Boltzmann constant; T—absolute temperature; n—the 'ideality' factor for thermionic emission and recombination processes at the semiconductor contact, which, in our case, is ≅ 1.6. As can be seen from the formula, an increase in temperature leads to an increase of the concentration of free carriers and current strength. By extrapolating the VAC curve with respect to the voltage axis, the contact potential differences (U_k) were calculated for different temperatures, 100 and 300 K, as of 0.6 V and 0.5 V, respectively.

To obtain the generation and recombination data in the region of volume charges in various temperature and voltage ranges, the VAC of the Ge–GeS:Nd heterojunction in the forward direction was studied. The dependence on a logarithmic scale of the VAC of the heterojunction in the forward direction is demonstrated in Fig. 2. The study of the graph shows that the dependence $I = f(U)$ obeys the law

$$I = I_0 \exp\left(qU/(nkT)\right),$$

where n is the coefficient characteristic of the p–n-junction, I_0 is the saturation current strength, q is the electron charge, k is the Boltzmann constant, and T is the absolute temperature. It was found from the analysis of the graph that, when the applied forward voltage value is of 0.05–0.25 V, the saturation current density decreases from $5 \cdot 10^{-7}$ A/sm^2 to $2 \cdot 10^{-8}$ A/sm^2. For the straight section of the graph, the coefficient n grows from 1.0 to 1.6. An analysis of the obtained data shows that the current flow mechanism in the Ge–GeS:Nd heterojunction and the generation–

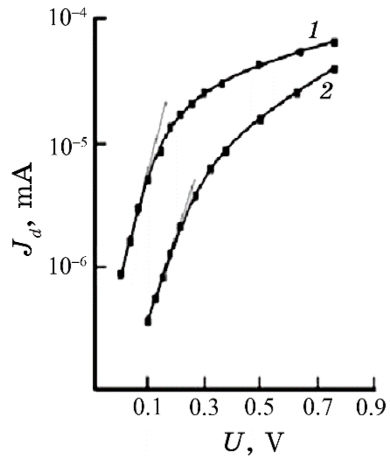

Fig. 2. Dark current–voltage curve of heterojunction Ge–GeS:Nd. *1*—100 K; *2*—300 K.

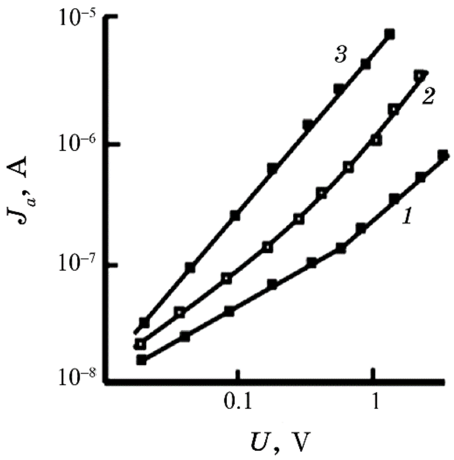

Fig. 3. Dark current–voltage curve of Ge–GeS:Nd heterojunction in the reversed direction: *1*—100; *2*—200; *3*—300 K.

recombination processes in the region of volume charges reconcile with the Sah–Noyce–Shockley theory [7]. The activation energy is calculated using the value of the slope angle of the $I_q = f(1/T)$–temperature curve plotted using VAC. As found, at low temperatures, $\Delta E_1 = 0.20$ eV, and at high temperatures, $\Delta E_2 = 1.04$ eV.

Figure 3 demonstrates VAC of the reverse direction of the Ge–GeS:Nd heterojunction at temperatures of 100 and 300 K on a logarithmic scale. It was revealed that the dark current depending upon voltage varies according to the $I \propto U^m$ law. It was found from the

$\ln I = f(U)$ relation that, at a temperature $T = 300$ K and a value of the applied reverse voltage $U < 6.8$ V, the indicator $m = 1.2$, and at $U > 6.8$ V, the indicator takes a larger value and is equal to $m = 1.4$. With a decrease in temperature to 100 K, the power coefficient decreases to $m = 1.1$. The reason for the decrease is the generation–recombination processes.

Thus, the analysis of the dark VAC of the Ge–GeS:Nd heterojunction shows that the generation recombination processes occurring in the region of volume charges have exponential character and explained on the basis of the Sah–Noyce–Shockley law. In the case of high temperatures ($T > 200$ K), with applied voltages $U < 0.1$ V, the exponential nature of the $I = f(U)$ relation indicates that the electrical resistance of the base material is less than the resistance of the shunting element.

As noted, one of the main challenges facing modern electronics is to obtain radiation-resistant solar converters that function normally in outside space. Compared to other structures, heterojunctions are characterized by high efficiency and radio stability [8]. The VAC obtained for this purpose of Ge–GeS:Nd heterojunctions were studied after irradiation with gamma rays at doses of 50 and 150 krad. The effect of various doses of gamma radiation on the dark VAC of the Ge–GeS:Nd heterojunction in the forward and reverse directions was revealed. Their analysis showed that, with an increase in the radiation dose, a change in the current strength in the forward direction obeys an exponential law. The exponential relation (function) is violated when the applied voltages are of 0.15–0.4 V. It is established that the current flowing mechanism in the Ge–GeS:Nd heterostructure depends on the filling mechanism of the depleted local trapping levels located in the forbidden region.

Another important factor affecting the electrical conductivity is the interaction of radiation defects arising under irradiation with existing lattice defects throughout the crystal. Under the influence of low-dose gamma rays (50 krad), the migration of radiation defects throughout the crystal leads to the formation of neutral defects and complex aggregates around Nd atoms [9]. Because of these processes, a certain order is created in the crystal. The existing order contributes to a decrease in carrier concentration and at the same time a decrease in current strength. These processes depend on the temperature of the sample and on the electrical voltage applied to it. The formation of second type defects occurs at irradiation doses of the order of 150 krad. In this case, the process of creating defects also involves electrons formed because of the ionizing effect of gamma rays, the kinetic energy of which is close to the gamma-ray energy. Acceptor-type defects, which have arisen in this way, lead to an increase in the electrical conductivity of the crystal [10].

4. CONCLUSIONS

Thus, the following results were obtained from the analysis of the dark VAC of the *n*-Ge–*p*-GeS:Nd heterojunction in wide temperature ranges and radiation doses.

1. The mechanism of electrical conductivity connected with the processes of generation and recombination in the region of volume charges and at certain temperatures and the radiation dose obeys the Sah–Noyce–Shockley theory.

2. The consequences of deviation from the above rule are neutral defects, which arise because of the interaction of radiation defects with primary lattice defects at high temperatures and high doses of radiation.

3. Defects arising at radiation doses of $F < 50$ krad contribute to an increase in the concentration of free carriers in the structural base, as well as an increase of the dark current.

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