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Influence of the NaCl Dielectric Layer on the Electrical Properties of Graphite/n-$Cd_{1-x}Zn_xTe$ Schottky Diodes Fabricated by Transferring Drawn Graphite

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This paper reports the results of an investigation of the electrical properties of graphite/n-$Cd_{1-x}Zn_xTe$ Schottky diodes prepared by the transfer of dry drawn graphite films on $Cd_{1-x}Zn_xTe$ substrates. The $Cd_{1-x}Zn_xTe$ solid solution with low Zn content was grown by the Bridgman method at low cadmium vapor pressure and had a low resistivity $\rho \approx 10^2$ Ohm·cm. The values of the series R_s and shunt R_{sh} resistances of graphite/n-$Cd_{1-x}Zn_xTe$ and graphite/NaCl/n-$Cd_{1-x}Zn_xTe$ Schottky diodes were determined from the dependence of their differential resistance R_{dif}. The height of the potential barrier of graphite/n-$Cd_{1-x}Zn_xTe$ and graphite/NaCl/n-$Cd_{1-x}Zn_xTe$ Schottky diodes was determined by the extrapolation of the linear segments of the *I-V* characteristics at room temperature toward the interception with the voltage axis and was equal 0.63 eV and 1.12 eV, respectively. The largest value of the potential barrier height for the sample graphite/NaCl/n-$Cd_{1-x}Zn_xTe$ was achieved by the presence of the NaCl dielectric layer. The dominant mechanisms of charge transport through graphite/n-$Cd_{1-x}Zn_xTe$ and graphite/NaCl/n-$Cd_{1-x}Zn_xTe$ Schottky diodes were described in the scope of generation-recombination and tunneling models (for forward and reverse bias, respectively).

Keywords: Graphite, Structures, CdZnTe, *I-V* characteristics.

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1. INTRODUCTION

The use of unique physicochemical properties of graphite thin films (high electrical and thermal conductivity, transparency in the visible light emission, inertness to chemical action [1-3]) is a good prospect for creating new nanomaterials and electronic devices based on them [4].

Cadmium telluride (CdTe) and solid solutions based on it, in particular $Cd_{1-x}Zn_xTe$, are widely used for the fabrication of photodetectors, solar cells and detectors for X- and γ-radiation operating at room temperature and are widely used in medicine, industry, space and other fields [5]. The large atomic number of the components of cadmium telluride provides high quantum efficiency of detectors in the range of 30-500 keV and above. The large band gap allows these detectors to operate at room temperatures without additional cooling [6, 7]. Significant progress has been made in the technology of obtaining high-quality semi-insulating CdTe crystals with a long service life and high values of the mobility of electrons and holes and their lifetime [8]. However, during storage in air, semiconductor substrates are oxidized, and thin films are formed on their surface, usually with dielectric properties [9, 10]. Also, during the technological process when creating electronic devices, these films with dielectric properties can remain at the interface between two materials, which will change the electrical properties of the manufactured devices. The purpose of this work is to show the effect of the NaCl dielectric layer on the electrical properties of graphite/n-$Cd_{1-x}Zn_xTe$ Schottky diodes manufactured by transferring a drawn graphite film on a substrate.

In recent years, vacuum-free methods for producing thin films have attracted the attention of scientists, since they are cheaper. The cheapest of them for the fabrication of graphite films is the "pencil-on-semiconductor" method. In this method, a drawn graphite film is transferred onto a quartz substrate. A graphite film is first drawn on a soluble substrate (NaCl), and then transferred to a smooth surface of a quartz substrate, and a high-quality optical contact is formed [11].

2. EXPERIMENTAL PART

For the fabrication of heterostructures, $Cd_{1-x}Zn_xTe$ crystals with low Zn content were used, which were grown by the Bridgman method and had a low specific resistivity $\rho \approx 10^2$ Ohm·cm.

In accordance with the "pencil-on-semiconductor" method, substrates $15 \times 15 \times 2$ mm in size were first cleaved from a NaCl single crystal. One of the surfaces of the NaCl substrate was mechanically polished using a mixture of diamond powder with alcohol in order to create a rough surface for applying a graphite film.

Using a pristine graphite cylinder 1 mm in diameter, a homogeneous graphite film was drawn on the prepared surface of the salt substrate with a constant pressing force. Afterwards, the sample was carefully placed on the surface of distilled water so that the graphite film floated on top. In order to remove all residual salt, the film was transferred twice to new glasses of fresh distilled water. A floating film of graphite was transferred onto glass and quartz substrates (with a standard size of $10 \times 10 \times 0.5$ mm) to study the optical and electrical properties, and CdZnTe (with a standard size of $5 \times 5 \times 0.3$ mm) for the fabrication of Schottky diodes. The transferred film must be dried at 50 °C to remove the remaining water. As a consequence, a high-quality optical contact is formed be-

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tween the graphite film and the semiconductor surface due to van der Waal interaction.

The resulting graphite films possessed n-type conductivity (determined using a thermal probe), and their average thickness was 150 nm (measured using an MII-4 microinterferometer), they possessed an optical transmittance of 26.6 % at 550 nm (measured by a spectrophotometer CF-2000). The surface resistance of the obtained graphite films was 350 Ohm/□ at 300 K (measured using the four-probe method).

The current-voltage characteristics of the heterostructures were measured according to the standard method using a Keysight B2985A precision femto/picoampermeter in combination with a voltmeter Agilent 34410A.

3. RESULTS AND DISCUSSION

Fig. 1 shows the dark current-voltage characteristics of graphite/n-$Cd_{1-x}Zn_xTe$ Schottky diodes on a semilogarithmic scale. The investigated Schottky diodes have pronounced diode characteristics.

The intermediate layer of NaCl dielectric in the graphite/NaCl/n-$Cd_{1-x}Zn_xTe$ structure remained after the dissolution of the NaCl salt substrate in distilled water. In a solution of water with salt, on the surface of which a graphite film was floating, n-$Cd_{1-x}Zn_xTe$ substrates were dropped to transfer it. In all other cases, a graphite film was transferred several times into pure distilled water to rinse it from salt residues.

The values of the series and shunt resistances of Schottky diodes R_s and R_{sh} can be found from the voltage dependence of their differential resistance R_{dif} [12] (Fig. 2). It is seen that at low voltages, the differential resistance decreases linearly in semilogarithmic coordinates with increasing voltage. If the voltage increases further, the $R_{dif}(V)$ curves become saturated. The value of the series resistance R_s of heterojunctions can be determined by extrapolating the saturated segments of the $R_{dif}(V)$ curves toward the interception with the axis of the differential resistance.

The inset of Fig. 2 shows the forward branches of the current-voltage characteristic of graphite/n-$Cd_{1-x}Zn_xTe$ Schottky diodes.

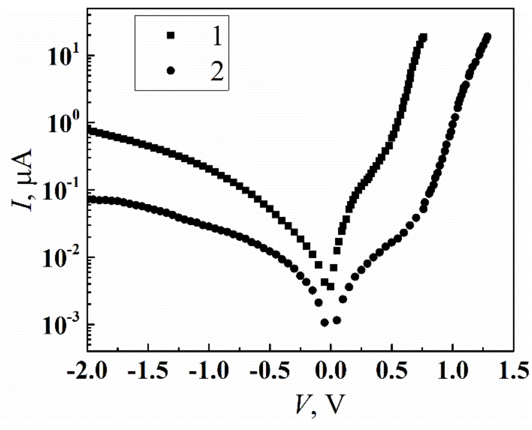

Fig. 1 – Dark current-voltage characteristics of graphite/n-$Cd_{1-x}Zn_xTe$ Schottky diodes on a semilogarithmic scale: sample No. 1 – graphite/n-$Cd_{1-x}Zn_xTe$; sample No. 2 – graphite/NaCl/n-$Cd_{1-x}Zn_xTe$

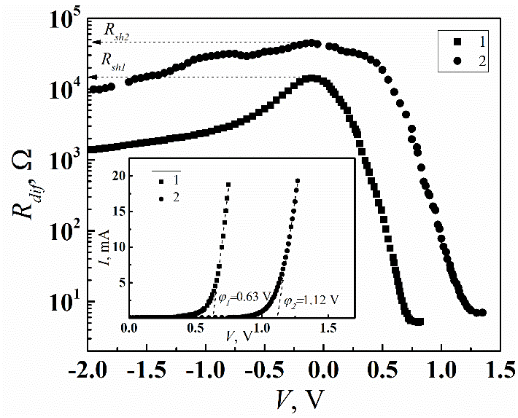

Fig. 2 – Voltage dependence of the differential resistance of Schottky diodes: sample No. 1 – graphite/n-$Cd_{1-x}Zn_xTe$; sample No. 2 – graphite/NaCl/n-$Cd_{1-x}Zn_xTe$

The height of the potential barrier is determined by extrapolating the linear segments of the I-V characteristics toward the interception with the voltage axis (see inset of Fig. 2). It should be noted that the potential barrier height for samples No. 1 and No. 2 at room temperature is equal to 0.63 eV and 1.12 eV, respectively. A greater value of the potential barrier height for sample No. 2 is achieved by using the NaCl dielectric layer. Analysis of the measured current-voltage characteristics of structures of the MIS (metal-insulator-semiconductor) type graphite/NaCl/n-$Cd_{1-x}Zn_xTe$ shows a significant increase in the height of the potential barrier in comparison with the electrical transition graphite/n-$Cd_{1-x}Zn_xTe$.

The value of the potential barrier height $\varphi_0 = 1.12$ V at a temperature of 295 K of graphite/NaCl/n-$Cd_{1-x}Zn_xTe$ structures indicates the possibility of their application as heterodiodes for operation at elevated temperatures and high loads.

Analysis of the forward branches of the I-V characteristics of graphite/n-$Cd_{1-x}Zn_xTe$ structures, built in a semilogarithmic scale with the effect of series and shunt resistances, shows that the dependence $\ln[I-(V-IR_s)/R_{sh}] = f(V-IR_s)$ consists of linear segments, indicating the exponential dependence of current on voltage. The values of the ideality factor $(\Delta\ln[I-(V-IR_s)/R_{sh}]/\Delta(V-IR_s) = e/nkT$, where n is the ideality factor) for both structures (Fig. 3 and Fig. 4) are determined. For sample No. 1, $n = 2.3$ in the voltage range $3\,kT/e < V < 0.2$ V and $n = 5.7$ in the voltage range $0.2 < V < 0.6$ V. For sample No. 2, $n = 6.5$ in the voltage range $3kT/e < V < 0.7$ V and $n = 3.1$ in the voltage range $0.7 < V < 1.1$ V.

Analysis of the forward passage of charge carriers through the energy barrier for sample No. 1 at forward bias ($3kT/e < V < 0.2$ V) shows that the values of the ideality factor $n = 2.3$, determined from the linear segment of the I-V characteristic $3kT/e < V < 0.2$ V (Fig. 3), indicate that the dominant mechanism of current transfer is generation-recombination processes in the space charge region via deep energy levels located in the middle of the band gap with the participation of energetically active surface traps located at the metallurgical interface of Schottky diodes [11, 13].

In the region of the forward bias ($0.2 < V < 0.6$ V), a constant slope of the dependences $\ln I = f(V)$ and a large value of the ideality factor $n = 5.7$ can be considered as evidence of the tunneling nature of the dominant current mechanism. Therefore, tunneling-recombination processes with the participation of surface states at the graphite/n-CdZnTe interface can be considered as the dominant mechanism of current transfer [11, 13].

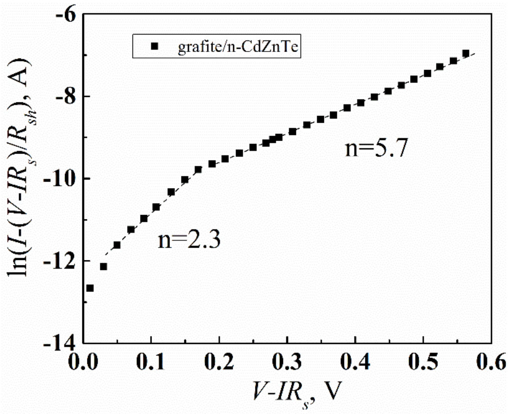

Fig. 3 – Forward branches of the *I-V* characteristics of heterojunction No. 1 – graphite/n-$Cd_{1-x}Zn_xTe$ on a semilogarithmic scale

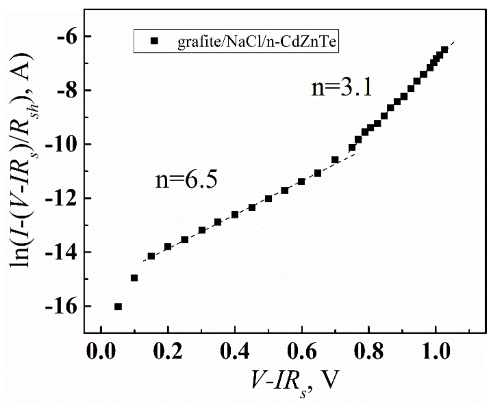

Fig. 4 – Forward branches of the *I-V* characteristics of heterojunction No. 2 – graphite/NaCl/n-$Cd_{1-x}Zn_xTe$ on a semilogarithmic scale

For sample No. 2 determined from the linear segment ($3kT/e < V < 0.7$ V) of the dependence $\ln I = f(V)$, the ideality factor is equal to $n = 6.5$, which can also be considered as evidence of the tunneling nature of the current transport mechanism. Therefore, we can assume that the dominant mechanism of current transfer in the voltage range $3kT/e < V < 0.7$ V is the model of multistep tunnelling recombination via surface states.

In the voltage range $0.7 < V < 1.1$ V, the values of the ideality factor $n = 3.1$ determined for the experimental dependences $\ln(I) = f(V)$ can be considered as evidence of the tunneling nature of the current transport mechanism, since a large value of the ideality factor is observed at sufficiently large forward bias, at which the space charge region is thin enough for direct tunneling, which is described by the Numen formula for the tunneling mechanism of current transfer.

In the case of an abrupt heterojunction, the tunneling current at reverse bias is governed by the following equation (1) [13]:

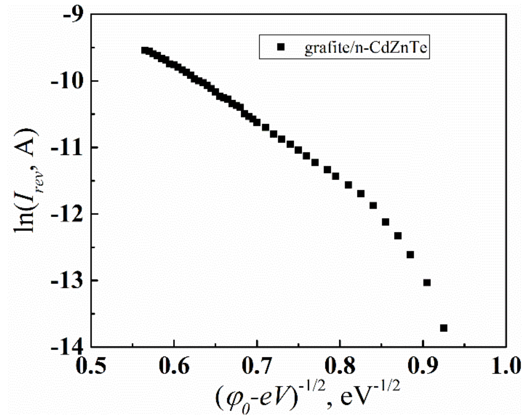

Fig. 5 – The tunneling mechanism of current transport through heterojunction No. 1 – graphite/n-$Cd_{1-x}Zn_xTe$ at reverse bias

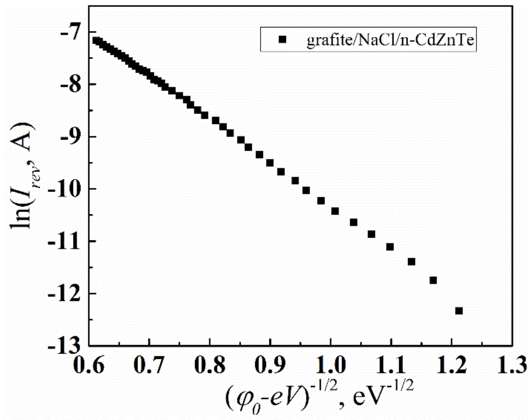

Fig. 6 – The tunneling mechanism of current transport through heterojunction No. 2 – graphite/NaCl/n-$Cd_{1-x}Zn_xTe$ at reverse bias

$$I_{rev} \approx \alpha_0 \exp\left(\frac{b_0}{\sqrt{\phi_0(T)-eV}}\right). \qquad (1)$$

According to equation (1), the linear *I-V* characteristics in the coordinates $\ln(I_{rev}) - (\varphi_0 - eV)^{-1/2}$ (see Fig. 5 and Fig. 6) prove the dominance of the tunneling mechanism of charge carrier transport at reverse bias $|V| > 3kT/e$ [13, 14].

4. CONCLUSIONS

Graphite/n-$Cd_{1-x}Zn_xTe$ Schottky diode was fabricated using the "pencil-on-semiconductor" technology.

The height of the potential barrier for graphite/n-$Cd_{1-x}Zn_xTe$ and graphite/NaCl/n-$Cd_{1-x}Zn_xTe$ samples (at room temperature) was determined to be 0.63 eV and 1.12 eV, respectively. It was found that a larger value of the potential barrier height for the graphite/NaCl/n-$Cd_{1-x}Zn_xTe$ sample was achieved by using the NaCl dielectric layer.

It was established that the mechanisms of current transport through graphite/n-$Cd_{1-x}Zn_xTe$ and graphite/NaCl/n-$Cd_{1-x}Zn_xTe$ Schottky diodes at forward bias are well described in the scope of the generation-recombination models. The main mechanism of charge carrier transport through heterojunctions at reverse bias is the tunneling through the space charge region via energy levels created by surface states.

It was found that the fabricated structures of the MIS type graphite/NaCl/n-$Cd_{1-x}Zn_xTe$, which have a built-in potential $\varphi_0 = 1.12$ V at a temperature of 295 K, make it possible to use the investigated MIS structure in the fabrication of high-quality electronic devices that can effectively operate at elevated temperatures and high loads.

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Вплив діелектричного шару NaCl на електричні властивості діодів Шотткі графіт/n-$Cd_{1-x}Zn_xTe$, виготовлених шляхом перенесення нарисованої плівки графіту на підкладки

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У статті представлені результати дослідження електричних властивостей діодів Шотткі графіт/n-$Cd_{1-x}Zn_xTe$, отриманих шляхом перенесення сухих графітових плівок на підкладки $Cd_{1-x}Zn_xTe$. Твердий розчин $Cd_{1-x}Zn_xTe$ з низьким вмістом Zn був вирощений методом Бріджмена при низькому тиску парів кадмію і мав низький опір $\rho \approx 10^2$ Ом·см. Значення послідовного R_s та шунтуючого R_{sh} опорів для діодів Шотткі графіт/n-$Cd_{1-x}Zn_xTe$ та графіт/NaCl/n-$Cd_{1-x}Zn_xTe$ визначали із залежності їх диференціального опору R_{dif}. Висота потенціального бар'єру для діодів Шотткі графіт/n-$Cd_{1-x}Zn_xTe$ та графіт/NaCl/n-$Cd_{1-x}Zn_xTe$ визначалася шляхом екстраполяції лінійних ділянок ВАХ до перетину з віссю напруги і становила 0,63 еВ та 1,12 еВ відповідно. Велике значення висоти потенціального бар'єру для зразка графіт/NaCl/n-$Cd_{1-x}Zn_xTe$ зумовлене наявністю діелектричного шару NaCl. Домінуючі механізми струмопереносу через діоди Шотткі графіт/n-$Cd_{1-x}Zn_xTe$ та графіт/NaCl/n-$Cd_{1-x}Zn_xTe$ добре описуються в рамках генераційно-рекомбінаційної та тунельної моделей (для прямого та зворотного зміщення відповідно).

Ключові слова: Графіт, Структури, CdZnTe, *I-V* характеристики.