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Schottky barriers based on graphite and InSe

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Schottky barriers based on the layered semiconductor InSe and graphite were fabricated by vacuum sputtering. Their I - V characteristics at different temperatures were studied. The electrical parameters of the structure were determined, and the current flow mechanisms were analyzed. The photosensitivity spectra of the barrier irradiated from the graphite side in the incident light energy range of 1.2–3 eB were obtained.

Keywords: indium selenide, graphite, Schottky barrier, I - V characteristics, photosensitivity.

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Introduction

Schottky barriers are formed at the interface between a metal and a semiconductor when the metal has a higher work function than the semiconductor. They serve as the basis for the fabrication of Schottky diodes, which belong to the class of low-power, high-speed semiconductor devices. Schottky diodes exhibit certain characteristics that distinguish them from conventional rectifier diodes based on the junction of two semiconductors. The main features include a fast switching time (low reverse recovery time) and a low forward voltage drop. These properties determine their field of application in electronics. In particular, Schottky diodes are widely used in high-speed computer circuits, where a short switching time is required to enhance the operating speed of the device. A promising direction for creating new generation electronic devices is the fabrication of Schottky barriers based on van der Waals semiconductors [1].

Graphite is a semimetal with a layered structure. The work function of graphite ($W = 5.04$ eV) exceeds the electron affinity of InSe ($\chi = 4.55$ eV). Therefore, the idea of creating Schottky diodes based on the InSe layered semiconductor, which has already been successfully used for the fabrication of Schottky-type junctions [2-4], and

graphite appears both interesting and promising. Certain steps have already been taken in this direction [5-7]. In [6], graphite/InSe heterostructures were assembled using the dry transfer technique, while in [6, 7] they were fabricated using a pencil. It was established that such heterostructures exhibit rectifying properties, and their photosensitivity is determined by light absorption in InSe.

In the present work, the graphite/ n -InSe heterostructures were obtained by vacuum deposition of graphite, which should ensure uniformity of the graphite films and stability of the electrical parameters of these structures.

I. Methodology of the experiment

InSe single crystals were grown by the Bridgman method from a melt of a nonstoichiometric composition $\text{In}_{1.03}\text{Se}_{0.97}$. The obtained crystals corresponded to the γ -polytype of InSe (space group C^{53}_v). The measured lattice parameters were $a = 4.003 \pm 0.001$ Å and $c = 24.9553 \pm 0.0006$ Å. Due to its layered structure, InSe can be easily cleaved along the layers (in the (0001) plane). For the investigations, plane-parallel InSe plates with dimensions of $6 \times 4 \times 1$ mm³ were cleaved. The plates had a mirror-like cleavage surface that meets standards for

heterostructures surfaces and requires no additional processing.

Graphite films were deposited onto the InSe surface by vacuum sputtering [8], which makes it possible to obtain heterostructures based on layered semiconductors. Graphite evaporation from the anode surface was carried out under electron-beam irradiation at next operating conditions: the positive anode voltage is 1000–2800 V, the current varying within 50–170 mA. The epitaxial process was conducted in a vacuum of approximately 10^{-4} Pa, while the temperature of InSe substrate during deposition could rise up to 600 K. Point contacts were applied to the graphite surface of the heterostructure using a conductive paste, while a continuous indium contact was formed on the opposite face of the InSe (Fig. 1).

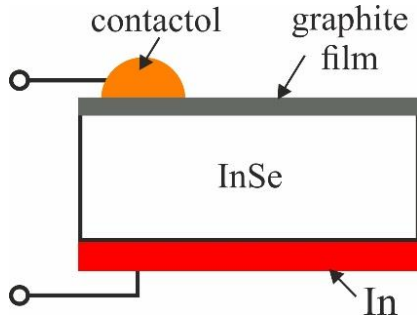


Fig. 1. Sketch of the device.

The current-voltage (I - V) characteristics of the graphite/ n -InSe heterostructures were studied using a Solartron 1255 measurement system. The temperature dependence of the I - V characteristics was measured within the temperature range of 247–333 K. The photosensitivity was investigated at room temperature using an MDR-3 monochromator with a spectral resolution of 2.6 nm/mm.

II. Results and discussion

To study n -InSe/graphite heterostructures, graphite films were deposited on an InSe substrate under different conditions. Electron microscopy studies of heterostructures obtained by pencil drawing [6, 7] revealed that the graphite layer has a porous structure and carbon atoms on the InSe surface are arranged in hexagonal rings with a size of 60–80 nm. It was shown in work [6] that the root-mean-square roughness of the InSe surface is 0.08 nm, while that of the graphite film is

0.387 nm. Atomic force microscopy images of graphite films deposited on InSe [8] shown that the graphite structures have an elongated shape with a size of less than 10 μm and a height of approximately 100 nm, and they are localized at the sites where planes of plastic deformation intersect the cleavage plane (0001) of InSe.

Fig. 2 shows the I - V characteristics of the graphite/ n -InSe heterostructures measured in the temperature range of 247–333 K. From the analysis of the forward I - V characteristics, the ideality factor $n = (e/kT)(dV/d\ln I)$ was determined in the voltage range of 0.1–0.8 V, giving values of $n = 9$ –10. For an ideal Schottky diode, n equals 1. The large value n obtained for the investigated heterostructures is attributed to the presence of structural defects at the interface formed during heterostructure fabrication. In particular, during preparation, local bending of the (0001) crystallographic planes in InSe may occur as a result of plastic deformation. The maximum surface height deviation of InSe surface does not exceed 0.36 nm [6].

The obtained values of the ideality factor exclude recombination and thermionic (over-barrier) current mechanisms and indicate a tunneling current mechanism. In this case, the forward I - V characteristics are described by the expression [9]:

$$I = B \cdot \exp(a(V - I \cdot R_S)) \quad (1)$$

where R_S is the series resistance, and B is the saturation current, which does not depend on the applied voltage.

The large series resistance (10–12 k Ω) along the crystallographic c axis is determined by the resistance of the bulk InSe crystal and is caused by the presence of two-dimensional stacking defects in the (0001) plane, which create energy barriers for carrier transport in this direction. The resistances of the electrodes, the thin frontal graphite layer, and the contacts are much smaller than the resistance of bulk InSe and thus do not significantly contribute to R_S . This is confirmed by the fact that R_S decreases with increasing temperature, as expected for semiconductors.

The barrier height Φ was obtained by extrapolating the linear parts of the forward I - V characteristics to the voltage axis. It equals approximately 0.6 eV and shows almost no temperature dependence. The calculated value of Φ can be expressed as [10]:

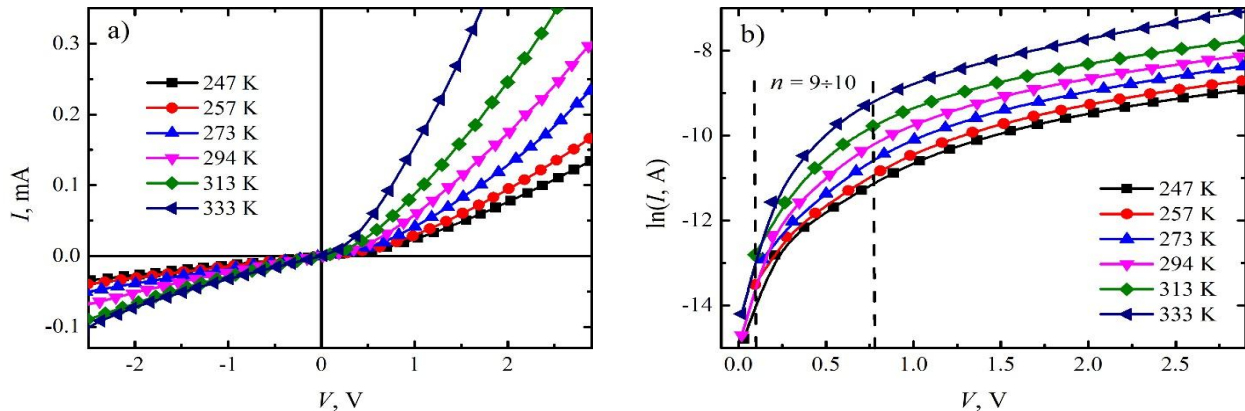


Fig. 2. I - V characteristics of the graphite/ n -InSe heterostructures.

$$\Phi = W_{\text{graphite}} - \chi_{\text{InSe}} \approx 0.5 \text{ eV}, \quad (2)$$

where W_{graphite} is work function of the graphite, χ_{InSe} is the electron affinity of the InSe.

Capacitance-voltage (C - V) measurements were carried out at frequencies of 100 and 250 kHz. Fig. 3 shows the experimental dependencies, extrapolation to the voltage axis yields $\Phi = 0.5$ V at 100 kHz. The experimental Φ values obtained from both I - V and C - V measurements of the graphite/ n -InSe heterostructures are consistent with the $\Phi = 0.5$ eV value calculated in [7] for the band diagram of the studied heterostructures.

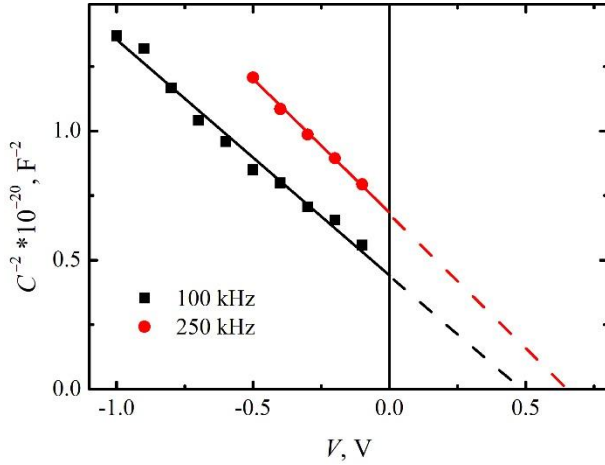


Fig. 3. C - V characteristics of the graphite/ n -InSe heterostructures.

The reverse I - V characteristics are described by the expression [9]:

$$I = a_0 \exp \left(-b_0 (\Phi - (V - IR_s)^{-1/2}) \right) \quad (3)$$

where a_0 and b_0 are voltage-independent parameters.

The experimental (see Fig. 2) and calculated (using Eqs. (1) and (3)) I - V characteristics coincide, confirming the tunneling mechanism of current transport in the n -InSe/graphite heterostructure.

The spectral dependence of the quantum efficiency of the graphite/ n -InSe heterostructures is shown in Fig. 4. Illumination was performed from the graphite side. Since the graphite film on the InSe surface transmits most of the incident light, the obtained photosensitivity spectra are determined by charge carrier generation processes in InSe. The heterostructures exhibit photosensitivity in the photon energy range of 1.2–3 eV, corresponding to the absorption spectrum of InSe. The long-wavelength edge of photosensitivity at $h\nu \approx 1.2$ eV is associated with the bandgap width of InSe ($E_g = 1.2$ eV), corresponding to fundamental absorption. The decrease in photosensitivity for $h\nu > 1.25$ eV may be related to excitonic absorption in InSe. In this region, the absorption coefficient k is approximately 10^3 cm^{-1} .

For photon energies $h\nu > 1.5$ eV, the photosensitivity increases, reaching a maximum at $h\nu \approx 2.1$ eV, which is caused by an increase in the absorption coefficient k up to 10^4 cm^{-1} in InSe. The half-width of the spectral quantum efficiency curve of the graphite/ n -InSe heterostructures is 1.4 eV. The subsequent decrease in photosensitivity is

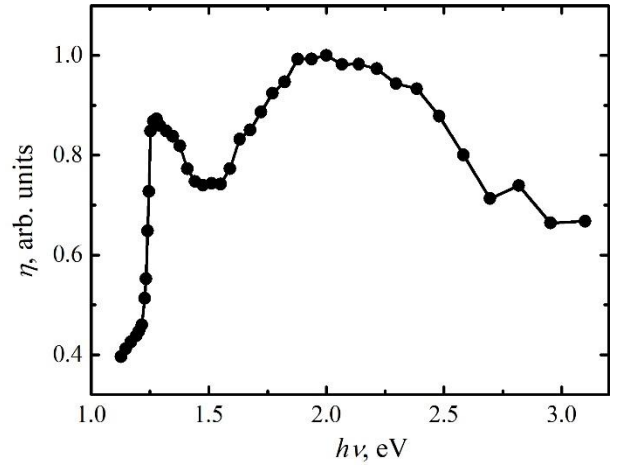


Fig. 4. Photosensitivity of the graphite/ n -InSe heterostructures.

determined by enhanced surface recombination. Short-wavelength radiation is absorbed closer to the surface; therefore, due to rapid surface recombination and the small diffusion length compared with the InSe thickness, the quantum efficiency decreases. The obtained spectral dependence of quantum efficiency qualitatively agrees with that reported in [8] for graphite nanostructures grown on InSe surfaces. This confirms that, within the investigated spectral range, the graphite film is transparent and the observed photosensitivity is determined by light absorption in InSe.

Conclusions

Schottky-type junctions of graphite/ n -InSe with stable electrical and photosensitive parameters were obtained by the vacuum deposition method. The perfection of the InSe crystals significantly affects the quality of the formed Schottky barriers.

Analysis of the forward I - V characteristics and the large ideality factor ($n \approx 9$ – 10) of the investigated heterostructures indicate a tunneling mechanism of current transport. The high series resistance R_s is associated with the presence of two-dimensional stacking defects in InSe. The Schottky barrier height Φ of the graphite/ n -InSe heterostructures, determined from both I - V and C - V measurements, is consistent with literature values for the energy-band diagram.

Reproducible photosensitivity spectra in the near-infrared region were obtained for the studied heterostructures, showing a maximum at $h\nu \approx 2$ eV and a spectral half-width $\delta_{1/2} \approx 1.4$ eV, which may have practical applications.

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Бар'єри Шотткі на основі графіту та InSe

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Методом розпилювання у вакуумі виготовлено бар'єри типу Шотткі на основі шаруватого напівпровідника InSe та графіту. Проведено дослідження їх вольт-амперних характеристик при різних температурах. Визначено електричні параметри структури, проаналізовано механізми протікання струму. Отримано спектри фоточутливості, опроміненого зі сторони графіту бар'єру в інтервалі енергій падаючого світла 1.2÷3 еВ.

Ключові слова: селенід індію, графіт, бар'єр Шотткі, вольт-амперні характеристики, фоточутливість.