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Research Article

Electronic Properties of FLG/InP Schottky Contacts

Fulya Esra Cimilli Çatır [1*], Murat Gülnahar [2]

[1*] Erzincan Binali Yıldırım University, Faculty of Vocational School, Departmant of Electronic and Automation, Erzincan, Turkey, (ORCID: 0000-0002-0757-3130), fcatir@erzincan.edu.tr

[2] Erzincan Binali Yıldırım University, Faculty of Vocational School, Departmant of Electricity and Energy, Erzincan, Turkey, (ORCID: 0000-0003-2801-3690), mgulnahar@erzincan.edu.tr

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Abstract

Graphene (Gr) is of great interest in the development of new electronic, photonic, and composite materials. The physical properties of Gr can vary depending on the number of layers, and this unique property makes it a potential material for different electronic applications. In this study, few-layer graphene (FLG) film was spin-coated onto the InP semiconductor surface and the FLG/n-InP Schottky contact was produced. The properties and quality of the FLG nano-film were determined by using Raman spectroscopy. Parameters such as ideality factor, barrier height, and series resistance of Schottky contacts were calculated using current-voltage (I-V) curves. With the Gaussian distribution, the mean ideality factor of the Gr/InP contacts was found to be $\langle n \rangle$=1,47, and the mean barrier height values were found to be $\langle \varphi b \rangle$=0.68 eV. The standard deviation values were calculated as σ=0.32 for the ideality factor and σ=0.06 eV for the barrier height. In addition, the series resistance values were calculated from the Cheung functions and were found to be in agreement with the literature. Finally, the current conduction mechanisms of the Gr/n-InP structure were revealed by examining the logarithmic I-V characteristics.

Keywords: Graphene, Gaussian distribution, InP, Raman spectrum.

FLG/InP Schottky Kontaklarının Elektronik Özellikleri

Öz

Grafen (Gr), yeni elektronik, fotonik ve kompozit malzemelerin geliştirilmesinde büyük ilgi görmektedir. Gr'nin fiziksel özellikleri katman sayısına bağlı olarak değişebilmekte ve bu benzersiz özelliği onu farklı elektronik uygulamalar için potansiyel bir malzeme yapmaktadır. Bu çalışmada InP yarı iletken yüzeyi üzerine birkaç katmanlı grafen (FLG) filmi döndürerek kaplandı ve FLG/n-InP Schottky kontakları üretildi. FLG nano filminin özellikleri ve kalitesi Raman spektroskopisi kullanılarak belirlendi. Schottky kontaklarının idealite faktörü, bariyer yüksekliği ve seri direnci gibi parametreler akım-gerilim (I-V) eğrileri kullanılarak hesaplandı. Gauss dağılımı ile Gr/InP kontaklarının ortalama idealite faktörü $\langle n \rangle$=1,47, ortalama engel yüksekliği değerleri ise $\langle \varphi b \rangle$=0,68 eV olarak bulundu. Standart sapma değerleri idealite faktörü için σ=0,32 ve engel yüksekliği için σ=0,06 eV olarak hesaplanmıştır. Ayrıca Cheung fonksiyonlarından seri direnç değerleri hesaplanmış ve literatür ile uyumlu bulunmuştur. Son olarak logaritmik I-V karakteristikleri incelenerek Gr/n-InP yapısının akım iletim mekanizmaları ortaya konulmuştur.

Anahtar Kelimeler: Grafen, Gauss dağılımı, InP, Raman spektrumu.

[*] Corresponding Author: fcatir@erzincan.edu.tr

1. Introduction

Schottky-based metal/organic/semiconductor structures have many different usage areas as a result of the developments in semiconductor circuit elements technology and their increasing importance day by day. These devices can generally be used as switching elements, microwave circuit elements, solar cells and detectors. Controlling the barrier height in the formation of a metal/organic/semiconductor is important for designing a high-performance electronic and optoelectronic circuit element. The performance and reliability of the circuit element are closely related to the geometrical and electronic properties of that material at the atomic scale.

Wide-bandgap III-V compound semiconductors for the fabrication of various electronic and optoelectronic devices have had important applications in recent years. The deposition of various organic inorganic films on InP semiconductors is still of interest for the fabrication of modern optoelectronics, microwave devices, and integrated circuits circuits (Cimilli et al, 2009a), (Cimilli Çatır, 2020)

Raman spectroscopy is a very effective method for the characterization of sp2 and sp3 hybrid carbon atoms. The electronic and vibrational properties of monolayer, bilayer and several layers of graphene can be easily investigated by resonance raman scattering (Ferrari et al., 2006).

Graphene is a two-dimensional, hexagonal structure of carbon atoms bonded together by hybridized sp2. These sheets are bonded with π bonded graphite. Graphene has interesting properties such as high electronic conductivity, thermal stability, and mechanical strength that researchers have been working on for a long time. However, the growth of single-layer graphene is critical for production, and it is not easy to control the number of graphene flakes during application. The spherical form of a single graphite layer is called 0D fullerene, and the 1D cylindrical form formed by curling around the edges is called a carbon nanotube. The 2-dimensional structure consisting of one or more graphite layers is called graphene. Few layers of graphene (FLG) in the literature: two to five layers; multilayer graphene, (MLG), two to ten layers; graphene nanoplatelet, (GNP): more than ten layers classified by name (Kauling et al., 2018). The physical properties of graphene material vary depending on the number of layers. For example, single-layer graphene has a sheet resistivity of about 2 KΩ/sq and an optical transmittance of about 97%. However, layer resistance and optical transmittance decrease with increasing layer number (Li et al., 2009).

In one of the first studies on the Gr/n-Si Schottky junction for solar cells, reported by Li et al. (2010), individual layers were mostly composed of single-layer, bi-layer, and several-layer graphene. Consisting of a coherent and continuous graphene sheet film coated on a patterned n-Si/SiO2 substrate with Au contacts, the device's I-V characteristics were highly rectifying (correction ratio 10+4-10+6) and diode ideality factor corresponding to n=1.57. It was almost linear in the 0.1-0.4 V range.

The spin coating method, which is easy to produce, strong, thin, smooth, conductive, and transparent films, is preferred compared to expensive and complex systems such as magnetron scattering, arc plasma, CVD, and spray pyrolysis. Hence, in this study, few-layered graphene (FLG) nano-film was deposited by spin coating onto an n-InP substrate, and then, Ag/FLG/n-InP Schottky diodes were fabricated. By using the forward bias current-voltage (I–V) characteristics, the ideality factor (n) and barrier height (Φb) of Ag/FLG/n-InP diodes were found by I–V and Cheung functions methods. The statistical Gaussian distributions of Ag/FLG/n-InP Schottky diode parameters were evaluated. The electrical and electronic properties of Ag/FLG/n-InP diodes were investigated.

2. Material and Method

First, the InP semiconductor sample was cut with a diameter of 1x1 cm and subjected to various processes in order to be cleaned from some organic and inorganic impurities (Cimilli, Sağlam, & Türüt, 2007). Then it was thoroughly washed with deionized water, dried, and made ready to form a film.

20 mg/ml graphene nano-powder and water dispersion were coated on the InP sample surface by spinning for 10 seconds at 500 rpm, 15 seconds at 1000 rpm, and 30 seconds at 5000 rpm. Next, the graphene films were dried at 100°C under nitrogen gas. The graphene film was subjected to a hydrazine hydrate treatment at 800°C under nitrogen flow and the graphene films were reduced again by a combination of annealing Then, In metal was vaporized on the back side of the sample and ohmic contacts were made (Cimilli et al., 2009b). Schottky contacts were produced by evaporating Ag metal on the graphene film surface with the help of a 0.5 mm diameter mask at about 10−6 mbar. The current–voltage (I-V) measurements for Ag/FLG/n-InP Schottky diodes were measured by using a Keithley 2400 picoammeter/voltage source at room temperature.

3. Results

Raman spectroscopy provides a facile way of structural and quality analysis of graphene materials. Fig. 1 shows Raman spectrum of the FLG film. Raman spectrum exhibited two strong and sharp peaks at 1375 cm−1 (D peak), 1590 cm−1 (G peak), and 2730 cm−1 (2D peak), being in agreement with spectral characteristic of graphene. These peak values show that the graphene-produced film is in the form of graphene, that is, it is not graphene oxide or graphite.

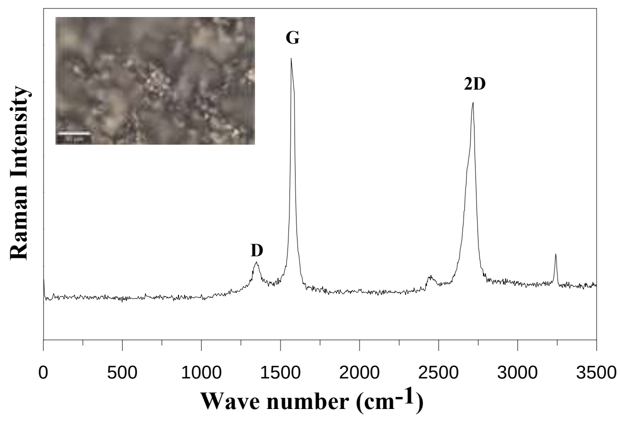

Fig. 1 Raman spectrum of FLG film

Raman spectroscopy is also a technique used to analyze single, double, several, or multilayer graphene films (Wang et al., 2008). The Raman spectrum of graphene is given in the literature as follows: D-peak at 1350 cm-1, G-peak at 1580 cm-1, and 2D-peak at ~2700 cm-1 (Lee et al., 2017). The intensity of these three values is used to separate the number of layers of the graphene film. The decrease in the intensity of the G peak and a sharper and narrower 2D peak is the most defining features of single-layer graphene. In multilayer graphene, on the other hand, the 2D peak expands and begins to deteriorate.

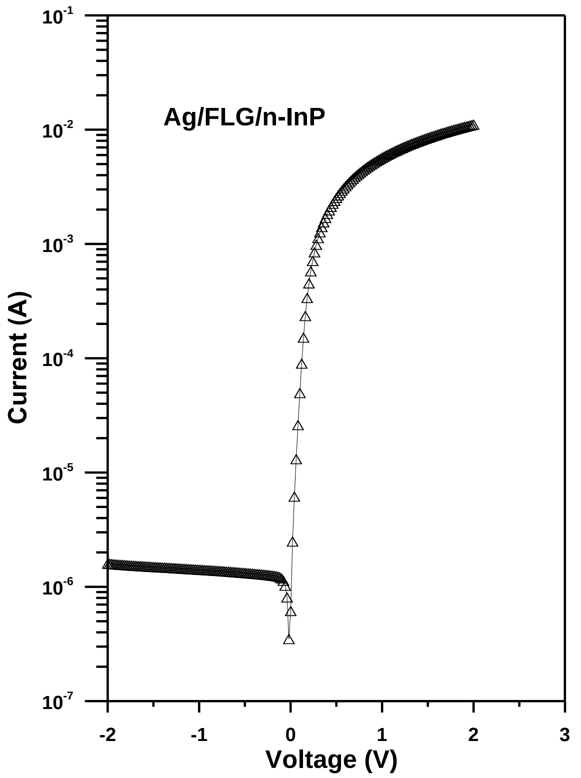

Fig. 2 Current-voltage (I-V) characteristics of Ag/FLG/n-InP Schottky diode

The presence of the D-peak gives a measure of the imperfection of the structure. That is, using the density of the D-peak, the number of microscopic defects in graphene can be explained (Singh et al., 2018). The Raman spectrum of monolayer graphene should not have a D-peak (Li et al., 2011). The presence of D-peak is attributed to the chemical doping of the graphene film and the presence of grain boundaries. The density ratio of D and G-peaks should not exceed 0.1 in a quality-produced graphene film. As shown in Figure 1, the ID/IG = 0.036 value was measured using Raman spectroscopy of manufactured graphene film. This value reveals that the defect density of the produced graphene film is low and relatively high-quality graphene sheets are produced (Li et al., 2011). In addition, the intensity of the 2D peak for monolayer graphene is given twice the intensity of the G peak in the literature. The density ratio of IG/I2D = 1.17 found in Figure 1 shows that the graphene film on the sample has few layers, but not a monolayer. As a result, we concluded that the graphene film we produced is few-layered graphene and our findings are in good agreement with the values reported in previous reports (Ferrari et al., 2006), (Wang et. al., 2008).

When the I-V measurement characteristics were examined, it was seen that all the produced diodes exhibited good rectification behaviour. The linear and semi-log I-V characteristics of a selected Ag/FLG/n-InP Schottky diode are shown in Figure 2. The FLG/n-InP structure showed good rectification properties and the rectifier feature of the diodes is in good agreement with the previously reported results (Baltakesmez et al., 2019), (Çetin & Ayyildiz, 2010), (Devi, Jyothi, & Reddy, 2012), (Bhaskar Reddy et al., 2009), (Cimilli et al., 2009b). The nonlinear I-V characteristic of Schottky diode behavior can be explained by thermionic emission theory (Bhaskar Reddy et al., 2009), (Gülnahar M, 2015). By using thermionic emission (TE) theory and forward I-V graph (Cimilli et al., 2009a), (Gülnahar M, 2015), the ideality factor values (n) of the diodes from the slope of the linear region and the barrier height (φb) values from the current axis intersection point were calculated, respectively.

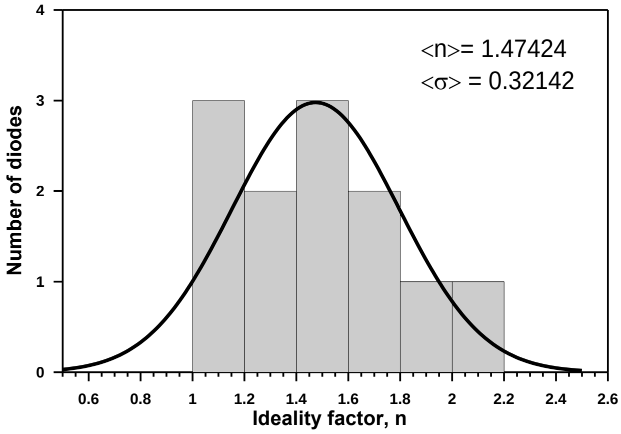

Fig. 3 Statistical Gaussian distributions of ideality factor values Ag/FLG/n-InP Schottky diode.

Statistical Gaussian distributions and Gaussian fits of n and φb are shown in Figures 3-4, respectively. Even if they are prepared identically, n and φb vary from diode to diode. Therefore, it is common practice to average these values (Sağlam, Cimilli, & Türüt, 2004). Ideality factor values were found to be between 1.04 to 2.14, with a mean idealite factor value of <n>=1.47. The standard deviation values were calculated as σ=0.32 for the ideality factor. The small standard deviation values were attributed to Ag/FLG/n-InP Schottky diodes approaching the classical ideal diode behaviour. The ideality factor values were calculated between 1 and 2 values for rectifier metal-semiconductor structures with organic and inorganic interfaces (Türüt, 2020). Balaram et al., (Balaram et al., 2018) studied CuO/n-InP Schottky diodes. The barrier height (φb) and ideality factor (n) were extracted through current voltage (I-V) and capacitance voltage (C-V) methods and the respective values were 0.66 eV (I-V)/0.80 eV (C-V) and 1.24, and 0.78 eV (I-V)/0.94 eV (C-V) and 1.62, respectively. Rajagopal Reddy (Reddy, Reddy, Padmasuvarna, & Narasappa, 2015) has reported that the ideality factor of Ru/Ti Schottky contact is found to be 1.19 for the as-deposited contact. The estimated ideality factor n values are 1.26, 1.59 and 1.64 for the contacts annealed at 200 °C, 300 °C and 400 °C, respectively. Our ideality factor values are in harmony with the classical semiconductor diodes in the literature. This means that the current transports at the Ag/FLG interface are approximately dependent on the thermionic emission theory.

Barrier height values range from 0.57 and 0.78 eV with the mean barrier height value of <φb>=0.68 eV. The standard deviation values were calculated as σ=0.06 eV for the barrier height. Devi et al. (2012) calculated the experimental values of as-deposited Au/Cu/n-InP Schottky contact has a barrier height of 0.64 eV from IV measurements and 0.76 eV from C-V measurements. Rajagopal Reddy et al. (2015) found the Schottky barrier heights of the Au/n-InP and Au/NiPc Schottky contacts as 0.59 eV (I–V)/0.71 eV (C–V) and 0.82 eV (I–V)/1.14 eV (C–V) with ideality factors of 1.22 and 1.83, respectively.

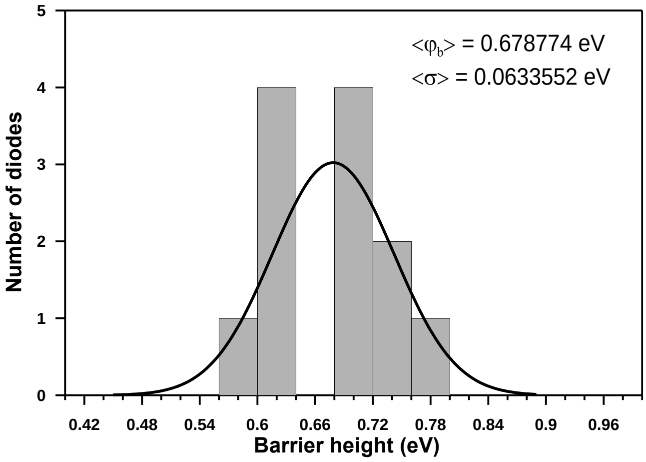

Fig. 4 Statistical Gaussian distributions of ideality factor values Ag/FLG/n-InP Schottky diode.

It is clearly seen that there is a significant change in the barrier height of the diode when compared with the above references due to the presence of the FLG interfacial layer. This can be explained by the chemical bonding of the FLG film to the InP semiconductor. Thus, it is concluded that the FLG interfacial layer causes a significant change in the interface states and the space charge region of the semiconductor, thereby changing the barrier height.

The series resistance (Rs) can be determined from the series resistance region of the I-V characteristics. The n, φb and Rs values were obtained from the equations below using the Cheung functions method again.

$$\frac{dV}{d(\ln I)} = \frac{nkT}{e} + IR_s \qquad (1)$$

$$H(I)=n\Phi b + IRs \qquad (2)$$

The n and Rs values were obtained from Eq. (1) as 1.20 and 9.37 Ω, respectively. Also, φb and a second Rs values were calculated from Eq. (2) as 0.73 eV and 10.62 Ω, respectively. As a result, it is seen that the barrier height, ideality factor and series resistance values calculated with the help of Cheung functions are in great agreement with the traditional I-V characteristics. This supports the accuracy of the calculations for Ag/FLG/n-InP diodes. In addition, these series resistance values calculated from the dV/d(lnI)-I and H(I)-I functions were found to be close to each other.

As mentioned above, one reason why the ideality factor is greater than 1 is the series resistance (Rs) effect, which causes the DC current voltage curves corresponding to high voltages to deviate from linearity. One of the important factors affecting the current-voltage characteristics of Schottky diodes is the neutral region resistance of the semiconductor body and is called the series resistance. Series resistance is a very important parameter of a metal-semiconductor Schottky diode and it is effective at high voltages. The existence of series resistance has been attributed to inhomogeneities at the metal-interlayer-semiconductor interfaces and/or to differences in surface morphology from region to region.

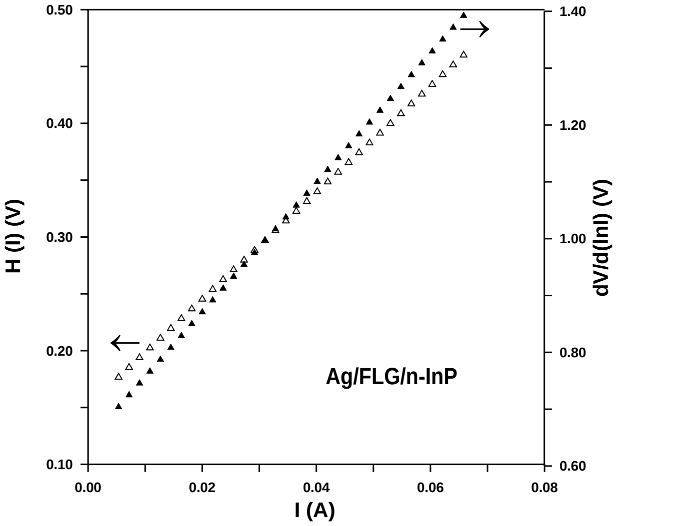

Fig. 5 Plot of dV/d(lnI) and H(I) versus I for Ag/FLG/n-InP Schottky diode calculated from Cheung functions

As can be seen from the above calculations, there are differences between the ideality factors and barrier heights obtained from the I–V and Cheung's methods. These differences are attributed to the fact that both methods calculate from different regions of the lnI-V plot. In the I–V method, the linear region is used for calculation, while the Cheung functions are influenced by the interface layer thickness, interface states, and bulk series resistance between metal and semiconductor.

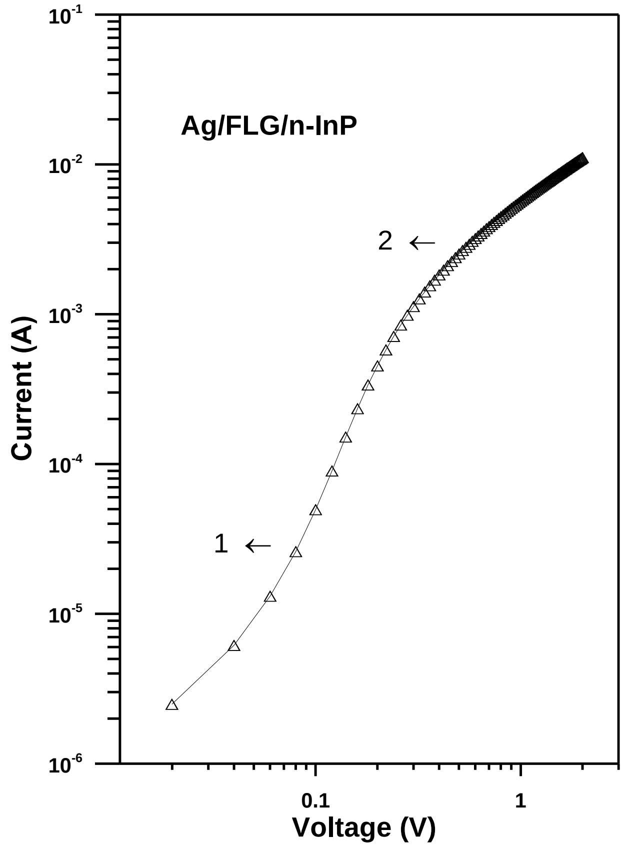

Fig. 6 Current-voltage (I-V) characteristics of Ag/FLG/n-InP Schottky diode in full logarithmic scale

In Figure 6, the current-voltage characteristics of the Ag/FLG/n-InP Schottky diode in the logI-logV scale was given. It is seen that the forward bias I-V plot of the device consists of two different linear regions. In Figure 6, the device exhibits ohmic behavior in the low voltage region, which is expressed as region 1 in the log-log scale. In this region, the current is proportional to the electric field. Many of the modern organic devices are based space charge limited conductivity (SCLC) interpreted by Mott in 1940 (Mott & Gurney, 1948). In the graph of the Ag/FLG/n-InP device on the logI-logV scale, there is a high voltage region also referred to as region 2. Region 2 is the limited space charge flow (SCLC) region.

4. Discussion

In this research, the electronic properties of Ag/FLG/n-InP device obtained from graphene, an organic material, with an inorganic n-type InP semiconductor were investigated. Basic diode parameters such as ideality factor and barrier height from I-V (current-voltage) measurements made at room temperature and in the dark were calculated by the TE method. From the graph obtained from the I-V measurements, it was observed that almost no current flows from the device in reverse feed, and the current values increase linearly at low voltage values in straight feed. In the calculation made from the linear region under straight feeding, it was observed that the twelve different devices obtained showed similar properties and the barrier height values varied between 0.77 eV and 0.84 eV. From these results, it was seen that Ag/FLG/n-InP device has a Schottky-type rectification feature and the FLG material provides a high barrier between Ag and n-InP. The forward bias logI-logV graph of the Ag/FLG/n-InP device was drawn and this graph exhibited two different regions that have been observed. These regions show ohmic conductivity at low voltages and space charge limited conductivity (SCLC) at high voltages. Ideality factor, barrier height, and series resistance values were calculated with the thermionic emission method of the Ag/FLG/n-InP device as well as the Cheung method. In the calculations made by the Cheung methods, the ideality factor and series resistance values of the Ag/FLG/n-InP device were different from the values obtained from the TE method. This difference is attributed to the calculation made by considering the different regions of the I-V graph, the series resistance effect, and the interface states.

5. Conclusions and Recommendations

Ag/FLG/n-InP Schottky diodes with a few layered graphene nanofilm on the interface were manufactured identically. Schottky barrier diode parameters such as ideality factor, barrier height, and series resistance obtained from the current–voltage (I–V) characteristics of Ag/FLG/n-InP Schottky diodes were studied. Ideality factor values range from 1.04 to 2.14 and barrier height values were found to be between 0.57 and 0.78 eV. The n value was obtained from the dV/d(lnI)-I plot as 1.20 and the φb value was calculated from H(I)-I as 0.73 eV. The series resistance values obtained from Cheung functions graphs were close to each other. The statistical Gaussian distributions of Ag/FLG/n-InP Schottky diode parameters were evaluated. The mean ideality factor of the Ag/FLG/n-InP contacts was found to be $\langle n \rangle = 1.47$, and the mean barrier height values were found to be $\langle \varphi b \rangle = 0.68$ eV. The standard deviation values were calculated as $\sigma = 0.32$ for the ideality factor and $\sigma = 0.06$ eV for the barrier height. The small standard deviation values were attributed to Ag/FLG/n-InP Schottky diodes approaching the classical ideal diode behavior. The forward bias logI-logV graph of the Ag/FLG/n-InP device exhibited that the dominant conduction mechanism is identified as the SCLC process. It is further shown that the traps are distributed uniformly in the forbidden band gap.

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