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# Optimization of the Electrical Characteristics of the Au/*n*-type InN/InP Schottky Diode Based on the Contact Technique of Different Diameters

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Optimization of electrical characteristics for electronic components is a main objective for the majority of recent research in this field. In this work, an experimental study of the Schottky diode is realized. This study is based on the proposal of a new measurement approach which concerns the Schottky contact technique by metallization of gold. The structure studied is composed of the InP substrate of selected section (1cm × 1cm), thickness of the order of 350 µm and cut out in the crystallographic plane (100). On this substrate, a thin layer of InN (2 nm) is engraved. We have used gold (Au) for two different values of diameters placed one next to the other in an alternative way; large ($d_L$ = 1.366038 mm) and small ($d_{Sm}$ = 0.815575 mm). Our measurement technique has allowed us to obtain the electrical characteristics of the Schottky diode *I-V*, *C-V* and *G-V*. These measurements allowed us to calculate the ideality factor ($n_L$ = 1.79, $n_{Sm}$ = 2.58), the saturation current ($I_{S_L} = 6.717 \times 10^{-4}$ mA , $I_{S_{Sm}} = 6.84 \times 10^{-4}$ mA), the potential barrier ($\Phi_{B_L}$ = 0.66 eV, $\Phi_{B_{Sm}}$ = 0.64 eV) and the series resistance ($R_{S_L}$ = 271 Ω, $R_{S_{Sm}}$ = 261 Ω) of our diode for the two diameters. The measurement results obtained on our Au/*n*-type InN/InP diode show the optimized electrical characteristics of the studied Schottky diode. In the logic of comparison of our work, we compared the obtained results for each contact and also the important results of other recent works for the same field of research. This comparison showed us a good agreement from the point of view of numerical values as well as the effectiveness of our proposed measurement approach.

**Keywords:** Conductance, Ideality factor, Potential barrier, Series resistance, Schottky diode.

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## 1. INTRODUCTION

In the last decade, the electronic components based on III-V semiconductors have known a remarkable development, including the components constituting the diodes (laser diodes, Schottky diodes) because this kind of diodes is commonly used in various devices for nanotechnology. III-V materials include alloys composed of one or more elements of column III of the periodic table associated with one or more elements of column V. The most common III-V components in the semiconductor industry are GaN, GaAs and InP. The physical properties of III-V materials that offer advantages and opportunities when performing in microelectronics compared to silicon are shown in [1, 2]. These materials have electron mobility approximately 10 times greater than that of Si because of their low effective mass.

The junction of a Schottky diode consists of a metal and a semiconductor where the electron is the majority carrier in both materials (the number of holes in the metal is negligible). It is this feature that is responsible for the exceptional characteristics of the Schottky diode. The electrical characterization (Schottky contact, the current-voltage measurement, the capacitance measurement and series resistance measurement) of Schottky diodes based on the InP and InN components has been the subject of several recent studies [3-7].

Measurements of electrical characteristics are often the major problem for the study of Schottky diodes. In this context, Ameur et al. realized two works for the Schottky diodes characterization based on InN/InP with mercury (Hg) metallization.

*I-V* and *C-V* characteristics of the first work [8] show that a channel formed by holes at the InN/InP interface is explained by the presence of two-dimensional electronic gas (2-DEG) in Schottky diode structure Hg/In/InP. In the second work, these characteristics show the effect of the InN interface layer and the $R_S$ series resistance on the various parameters of this structure [9]. Hadjadj et al. [10] studied the *I-V* characteristics of the same structure of the Schottky diode InN/InP by the metallization of gold (Au) as a Schottky contact.

In this work, we will present a detailed experimental study of the Schottky diode electrical characteristics based on InN/InP, with a metallization that is made from gold (Au). We will propose a new measurement technique that articulates the use of different values for the metal/semiconductor contact diameters. This technique will allow us to obtain current-voltage *I-V*, capacitance-voltage *C-V* and conductance-voltage *G-V* characteristics. For the diameters contact, we will choose two different values: large and small ($\Phi_L$ = 1.366038 mm, $\Phi_{Sm}$ = 0.815575 mm). We will extract the different parameters of this diode for these two values such as the ideality factor ($n$), the saturation current ($I_S$), the series resistance ($R_S$) and the potential barrier ($\Phi_B$). Both *C-V* and *G-V* characteristics will be obtained at the frequency $f$ = 1 MHz.

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## 2. EXPERIMENTAL TECHNIQUE

### 2.1 Technological Procedure

The *n*-type indium phosphide (InP) substrates used are from industry (crystal impact). They are in the form of circular plates with a diameter of 50 mm and a thickness of the order of 350 μm. They were made by drawing Czochralski (under encapsulation) and are cut in the crystallographic plane (100) in monocrystalline ingots. These platelets used are doped with "*n*" type carriers ($N_D$ is of the order of $10^{16}$ cm$^{-3}$). These platelets are delivered with a mechanochemical polishing which gives them an optical quality. For our work, we used an InP substrate of (1×1) cm$^2$ for length and width and 350 μm for thickness.

The prolonged residence of the samples in the atmosphere causes the pollution of the surface by various impurities (carbon, oxide and fats mainly). Therefore, it is necessary firstly to perform a chemical cleaning of the surfaces of these substrates. The cleaning method consists of successive baths of alcohol, sulfuric acid and bromine, then ionically with argon ions; the deposition of $N_2$ is made under ultra-high vacuum with a discharge nitrogen source on InP heated to about 250 °C. This will allow nitrogen to bind with the metallic indium that is on the surface of InP after ion bombardment to thereby form a layer of InN. This layer is very thin, it is of the order of a few Angstroms (15 to 20). So, to clean the samples just rinse them with methanol and gently dry them without rubbing them because we risk damaging the InN layer that exists on the InP substrates. For the metallization of the samples, we realized a mask of two different diameters to obtain the metal contacts to make our various measurements. The ohmic and Schottky contacts were made by Au evaporation on the substrate at $5\cdot10^{-6}$ mbar and the ohmic sides of the samples for 10 min in $N_2$ atmosphere. The two contact surfaces of the structure are $1.46\cdot10^{-2}$ cm$^2$ and $0.521\cdot10^{-2}$ cm$^2$. In addition, the thickness of the active region of the diodes was calculated as the order of 80 to 100 nm. To electrically characterize our Schottky structures, we used the direct and inverse measurements of current according to the voltage (*I-V*) with the measuring instrument which is Semiconductor Parameter Analyzer HP 4156A and measurements of the capacitance as a function of the voltage (*C-V*) and the conductance according to the voltage (*G-V*) with the measuring instrument which is LCRmeter HP 4284 A at high frequency of 1 MHz. The structure to be studied is illustrated in Fig. 1.

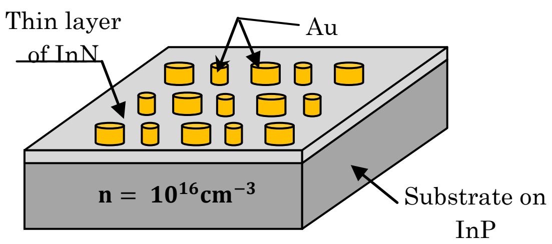


**Fig. 1** – Sample to study

Our sample treated in the laboratory is shown in Fig. 2. In the figure, the Schottky contact (Au) is in yellow, the grains in blue show our substrate + thin film structure of InN.

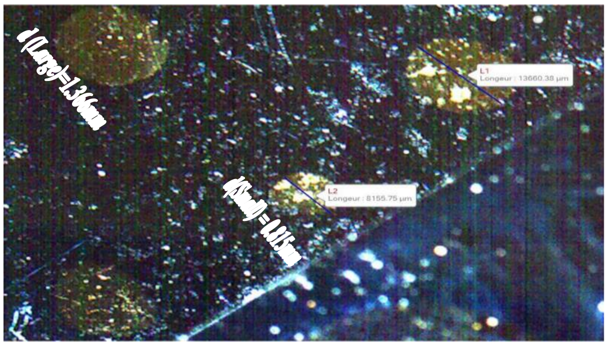

**Fig. 2** – Top view of the Au/*n*-type InN/InP structure for both diameters

## 3. RESULTS AND DISCUSSION

### 3.1 Electrical Characterization

#### 3.1.1 I-V Characteristic

The current of the Schottky diode is given by [11]

$$I = I_S\left[\exp\left(\frac{qV}{nkT}\right)-1\right], \qquad (1)$$

where is the electronic charge, $k$ is the Boltzmann constant, $T$ is the absolute temperature in Kelvin, $n$ is the ideality factor, $V$ is the polarization voltage applied and $I_S$ is the saturation current given by the following expression:

$$I_S = SA^*\cdot T^2\exp\left(\frac{-q\Phi_B}{kT}\right), \qquad (2)$$

where $S$ is the contact surface, $\Phi_B$ is the potential barrier and $A^*$ is the effective constant of Richardson ($A^* = 9.4$ A/cm$^2$ K$^2$).

The potential barrier $\Phi_B$ at zero polarization voltage ($V = 0$) is given by the following expression:

$$\Phi_B = \frac{kT}{q}\ln\left(\frac{SA^*T^2}{I_S}\right)\exp\left(\frac{-q\Phi_B}{kT}\right). \qquad (3)$$

The Schottky diode current-voltage (*I-V*) characteristic is given in Fig. 3.

Fig. 3 shows the *I-V* characteristic of the direct and inverse polarization of the Au/*n*-type InN/InP structure to measure both contact diameters (large and small). Here $I_L$ is the current of the large diameter and $I_{Sm}$ is the current of the small diameter. The variation of the current according to the polarization voltage (from – 2 V to + 2 V) shows an exponential characteristic for the positive voltages, which allows us to say that our measured structure is a Schottky diode. It may also be noted that the current for the small diameter is greater than that of the large diameter (for positive voltages), which is shown in the curves of Fig. 3. Also in this figure, the influence of the contact surface on the current is well shown by the curve in red, which justifies that the direct current of the structure is inversely proportional to the contact surface.

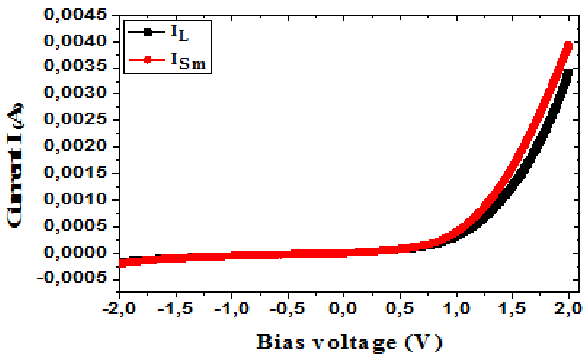


**Fig. 3** – Schottky diode current-voltage characteristic

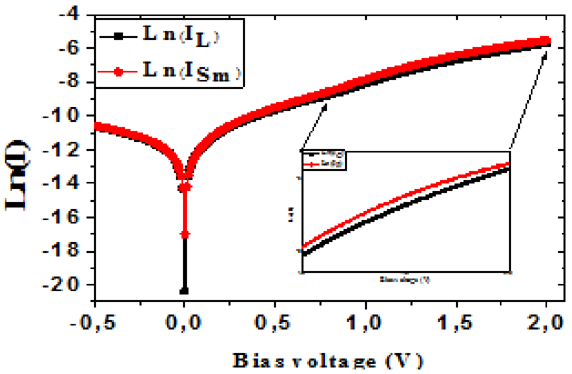


**Fig. 4** – ln*I*-*V* characteristic of the Au/*n*-type InN/InP Schottky diode

The increase in the height of the potential barrier is mainly responsible for the decrease in the inverse current polarization of the diode. The direct polarization *I*-*V* characteristic of Schottky diodes could be considerably deviated from linearity due to some high voltage factors. One of these factors is the series resistance $R_S$. This resistance is influenced by the presence of the interface layer between the metal and the semiconductor and leads to non-ideal direct current-voltage polarization traces. When the applied voltage is sufficiently large, the effect of $R_S$ can be seen at the nonlinear regions of the direct polarization *I*-*V* characteristics.

From (1), the ideality factor $n$ is given by

$$n = \frac{q}{kT}\left(\frac{dV}{d(\ln I)}\right). \tag{4}$$

The ideality factor can be determined from the slope of the linear region for the direct polarization characteristic ln*I*-*V*. $n$ is equal to one ($n = 1$) for an ideal diode, which means that the current flow is dependent on the thermionic emission. However, the ideality factor $n$ is usually a value greater than one. High values of $n$ can be attributed to the presence of InN thin film or to inhomogeneity barrier, and thus depends on polarization voltage. On the logarithmic (Neperian) scale, the ln*I*-*V* characteristic is shown in Fig. 4.

Fig. 4 shows the ln*I*-*V* characteristic for a polarization voltage ranging from – 0.5 V to 2 V. The intersection of the tangent of this characteristic and the line ($V = 0$) allows us to extract the two ideality factors for the large and small diameters respectively ($n_L = 1.8$ and $n_{Sm} = 2.5$) and the saturation currents which are $I_{S_L} = 6.717\times10^{-4}$ mA and $I_{S_{Sm}} = 6.84\times10^{-4}$ mA.

From expression (2), the height of the potential barrier of each diameter can be determined. The potential barrier values for large and small diameters are $\Phi_{B_L} = 0.66$ eV and $\Phi_{B_{Sm}} = 0.64$ eV, respectively.

The series resistances $R_S$ were also calculated according to a method developed by Cheung and Cheung and confirmed by Werner. Cheung's functions can be written as follows

$$\left(\frac{dV}{d(\ln I)}\right) = \frac{nkT}{q} + IR_S. \tag{5}$$

The *H*(*I*) characteristic as a function of the current is given by relation (6) as follows:

$$\begin{cases} H(I) = V - \left[n\frac{kT}{q}\ln\left(\frac{I}{S\cdot A^{*}T^{2}}\right)\right], \\ H(I) = n\Phi_B + IR_S. \end{cases} \tag{6}$$

Fig. 5 shows the variation of *H*(*I*) as a function of the current, where $H(I_L)$ is the characteristic for the large diameter and $H(I_{Sm})$ is the characteristic for the small diameter. From the *H*(*I*) characteristic, we can extract the values of the series resistances for the two contacts with different diameters. These values are $R_{S_L} = 271$ Ω for the large diameter and $R_{S_{Sm}} = 261$ Ω for the small diameter.

Our measurement results show that the saturation current of our *n*-type InN/InP Schottky diode with Au contact is low compared to the results of other works.

The electrical characteristics for the Hg/InN/InP Schottky contact in [8, 9] and Au in [10] are shown in Table 1.

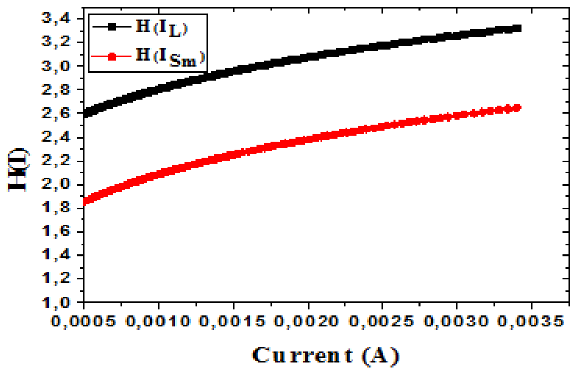


**Fig. 5** – *H*(*I*) characteristic of the Au/*n*-type InN/InP Schottky diode

**Table 1** – Au/*n*-type InN/InP Schottky diode parameters

| Schottky diode | $I_0$ (A) | $n$ | $R_S$ (Ω) | $\Phi_B$ (eV) | Refs. |
|---|---|---|---|---|---|
| Hg/InN/InP | $4.47\cdot10^{-6}$ | 2.10 | $1.4\cdot10^{3}$ | 0.55 | [8] |
| Hg/InN/InP | $3.36\cdot10^{-6}$<br>$6.81\cdot10^{-6}$ | 2.56<br>2.52 | $10.9\cdot10^{3}$<br>$10.9\cdot10^{3}$ | 0.54<br>0.59 | [9] |
| Au/InN/InP | $1.33\cdot10^{-4}$ | 3.31 | 25 | 0.46 | [10] |
| Au/InN/InP-L | $6.717\cdot10^{-7}$ | 1.79 | 271 | 0.66 | This work |
| Au/InN/InP-Sm | $6.84\cdot10^{-7}$ | 2.58 | 261 | 0.64 | This work |

### 3.1.2 *C-V* Characteristic with $f = 10^6$ Hz

The characteristic giving the capacitance as a function of the voltage is shown in Fig. 6.

Fig. 6 shows the characteristic of parallel capacitance according to the voltage for both diameters. From the measurements made on the two contacts, we can notice that this characteristic has a Schottky diode behavior. In the same figure, we also note that for negative voltages, both capacities have low values. They begin their increase from the positive tension. It is also noted that the capacity for the large diameter has values greater than those of the small diameter, which justifies the influence of the diameter on the contacts and on the surface state. Therefore, we can say that the capacity of our structure is proportional to the contact diameter. The maximum value of the capacity for large diameters is of the order of 450 pF and for the other diameters it is of the order of 250 pF.

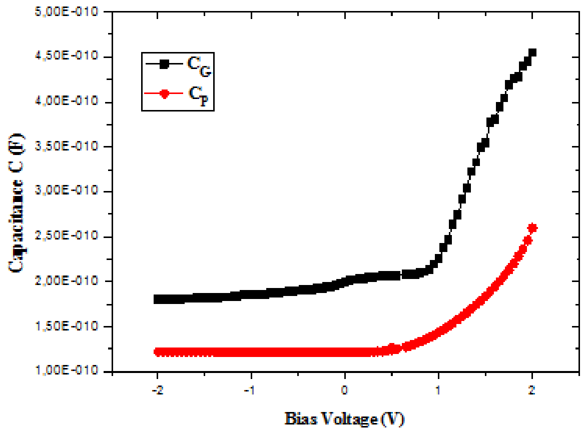


**Fig. 6** – Capacitance-voltage characteristic of Au/*n*-type InN/InP Schottky diode

From the *C-V* characteristic we can extract the $C^{-2}$-*V* characteristic which is represented in Fig. 7.

Fig. 7 shows the $C^{-2}$-*V* characteristic for both diameters, $C_L^{-2}$ for the large diameter and $C_{Sm}^{-2}$ for the small diameter. From the curves in Fig. 7, it is possible to deduce the values of the diffusion voltage for the two diameters, respectively, $V_{D_L} = 1.6$ V and $V_{D_{Sm}} = 2.2$ V. These two large diffusion voltage values are due to defects in our structures and no uniformity of the InN layer and the interface state. The capacity of the Schottky diode varies according the bias voltage [12]

$$1/C^{-2} = \frac{2(V_D - V)}{q\varepsilon N_D S^2}, \quad (7)$$

where $N_D$ is the concentration of the ionized donor (InP substrate), $V_D$ is the diffusion potential, $\varepsilon_s = 12.1\,\varepsilon_0$ is the permittivity of InP ($\varepsilon_0 = 8.85 \times 10^{-12}$ F/m). The results of the various measurements are shown in Table 2. The calculated doping is lower than that of the InP concentration. This reduction could be due to the traps associated with the InN film on the surface (is not intentionally doped). The diffusion potential $V_D$ and the concentration of the large diameter are smaller than that of the small diameter.

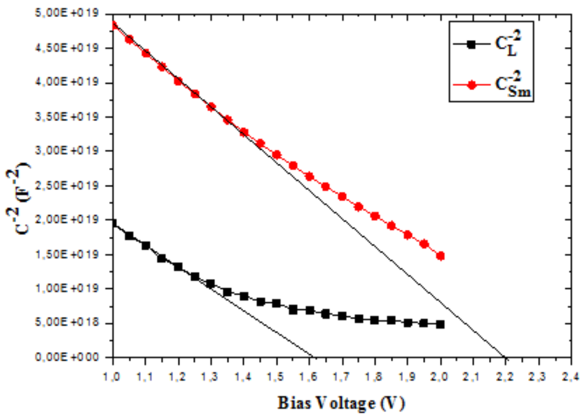


**Fig. 7** – The $C^{-2}$-*V* characteristic of the Au/*n*-InN/InP Schottky diode

**Table 2** – Electrical parameters calculated by the *C*(*V*) method for the two contact diameters

| Concentration and diffusion potential | Large diameter ($d_L$) | Small diameter ($d_{Sm}$) |
|---|---|---|
| $N_D$ (cm$^{-3}$) | $3.5 \times 10^{14}$ | $1.39 \times 10^{15}$ |
| $V_D$ (V) | 1.6 | 2.2 |

### 3.1.3 *G-V* Characteristic for $f = 10^6$ Hz

The conductance calculation technique is based on the conductance losses resulting from the exchange of majority carriers between the interface states and the majority carrier band of the semiconductor when a small alternating signal is applied to the semiconductor devices. The conductance-voltage *G-V* characteristics of our Au/*n*-InN/InP structure for a constant frequency $(f = 10^6$ Hz$)$ according to the different contact diameters are shown in Fig. 8.

Fig. 8 shows the *G-V* characteristic where *G* is the conductance measured at the frequency of 1 MHz. We can notice that the conductances are low for the negative voltages and they have important values (for slight differences) for the positive voltages. The variation of the two conductances shows a growing form as a function of the polarization voltage. The conductance for large diameters is greater than that of small diameters because of the contacts as it appears in Fig. 8. A slight increase in conductance can be attributed to the increase in the net concentration due to the ionized doping or to the excess of carriers generated. The influence of the contact surfaces is always involved, whereas the conductance for large diameters is $G_L(1\text{ V}) = 3.05 \times 10^{-3}$ Siemens and $G_{Sm}(1\text{ V}) = 2.31 \times 10^{-3}$ Siemens for small diameters. A comparison of the conductance values obtained by our approach with other works is shown in Table 3.

**Table 3** – Comparison of our conductance with other works

| Different works | Conductance |
|---|---|
| [13] | $G/\omega(1\text{ V}) = 2.9 \times 10^{-5}$ F |
| [14] | $G/\omega(1\text{ V}) = 6 \times 10^{-6}$ F |
| This work | $G_L(1\text{ V}) = 3.05 \times 10^{-3}$(Siemens) |
| This work | $G_{Sm}(1\text{ V}) = 2.31 \times 10^{-3}$(Siemens) |

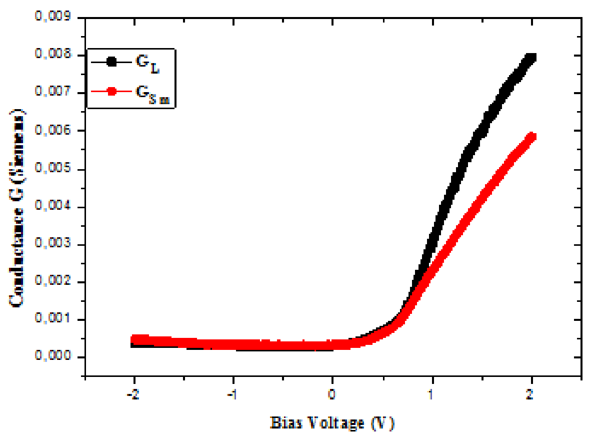


**Fig. 8** – Conductance-voltage characteristic of Au/*n*-type InN/InP Schottky diode

### 3.1.4 The Series Resistance of Au/*n*-type InN/InP Schottky Diode

The series resistance of metal-semiconductor devices can be subtracted from measured capacitance and conductance measurements in the high frequency high accumulation region. The series resistance according to the diameter of the contact can be obtained from the measurements of the curves $(C-V-d)$ and $(G-V-d)$ at constant frequency ($f$ = 1 MHz) [15]

$$R_S = \frac{G_{ma}}{G_{ma}^2 + (\omega G_{ma})^2}, \tag{8}$$

where $G_{ma}$ and $C_{ma}$ are the values of the conductance and the capacity obtained in the high frequency high accumulation region and $\omega = 2\pi f$.

The Fig. 9 shows the variation of the series resistance as a function of the bias voltage for the two large and small diameters, where $R_{S_L}$ for the large diameter and $R_{S_{Sm}}$ for the small diameter.

The curves in Fig. 9 describe the series resistance-voltage characteristics ($R_S$ – $V$) for the two diameters of the structure for constant frequency ($f$ = 1 MHz). The series resistance depends on both the contact diameter and the polarization voltage. Note that for the two curves Fig. 9 gives a peak at a particular voltage which decreases with increasing diameter of the contact. The variation of the series resistance as a function of the voltage and the diameters of the contact can be attributed to the particular distribution density of the interface states and interfacial layer. As shown in Fig. 9, the series resistance increased after decreasing the diameter of the contact. According to the figure, the series resistances are $R_{S_L}$ = 111.58 Ω of large diameter and $R_{S_{Sm}}$ = 168.16 Ω of small diameter.

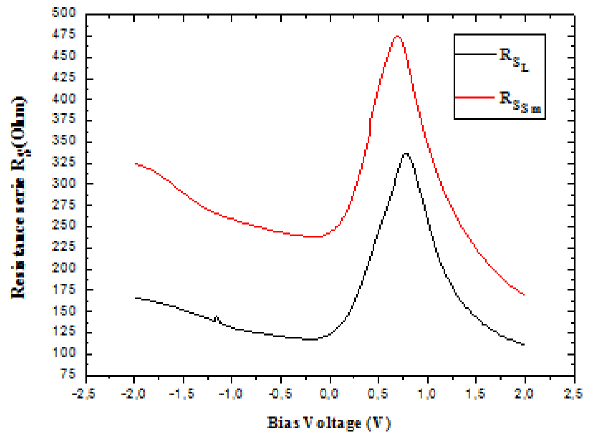


**Fig. 9** – The resistance-voltage-diameter curves in series of the Au/*n*-type InN/InP diodes

A comparison of the series resistance values obtained by our approach with other works is shown in Table 4. It is worth mentioning here that our results are in good agreement with those of Ref. [13]. Series resistances are close to each other with a slight magnitude order.

**Table 4** – Comparison of our series resistance with other works

| Different works | Series resistance |
|---|---|
| Au/Ni/*n*-6H-SiC [13] | $R_S$(0.5 V) = 115.65 Ω |
| Au/Ni/*n*-4H-SiC [13] | $R_S$(0.5 V) = 51.11 Ω |
| This work | $R_{S_L}$(0.78 V) = 336.30 Ω |
| This work | $R_{S_{Sm}}$(0.70 V) = 475.19 Ω |

## 4. CONCLUSIONS

In this work, a new technique of contact is proposed to optimize the electrical characteristics of the Schottky diode. The use of contacts of different diameters, large and small, allowed us to show the impact of our approach on these electrical characteristics. We used Au/*n*-type InN/InP as the structure to characterize. The measurement results of the current-voltage (*I-V*), the capacitance-voltage (*C-V*) and the conductance-voltage (*G-V*) characteristics for the two proposed contact diameters (at the frequency of 1 MHz) show optimized values for the potential barrier, the ideality factor and the series resistance. According to our results, we can conclude that the effect of the contact diameter is remarkable on the Schottky electrical characteristics, while the contacts of small diameter show high direct current and low capacitance and conductance. A comparison with other works may justify the effectiveness of our proposed approach in this work.

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## Оптимізація електричних характеристик діода Шотткі Au/*n*-InN/InP на основі контактної техніки різних діаметрів

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Оптимізація електричних характеристик електронних компонентів є основною метою більшості сучасних досліджень у цій галузі. У роботі проведено експериментальне дослідження діода Шотткі. Дослідження базується на застосуванні нового підходу вимірювання, який використовує контактний метод Шотткі при металізації золота. Досліджувана структура складається з підкладки InP обраного перерізу (1 см × 1 см), товщиною порядка 350 мкм, вирізаною в кристалографічній площині (100). На цій підкладці вигравіруваний тонкий шар InN (2 нм). Ми використовували золото для двох різних значень діаметрів, розміщених один біля іншого довільним чином; великий ($d_L$ = 1,366038 мм) і малий ($d_{Sm}$ = 0,815575 мм). Наша методика вимірювання дозволила отримати такі електричні характеристики діода Шотткі як *I-V*, *C-V* і *G-V*. Вимірювання дозволили обчислити коефіцієнт ідеальності ($n_L$ = 1,79, $n_{Sm}$ = 2,58), струм насичення, потенційний бар'єр ($\Phi_{B_L}$ = 0,66 еВ, $\Phi_{B_{Sm}}$ = 0,64 еВ) і послідовний опір ($R_{S_L}$ = 271 Ω, $R_{S_{Sm}}$ = 261 Ω) для двох різних діаметрів. Результати вимірювань, отримані на нашому діоді InN/InP Au/*n* типу, показують оптимізовані електричні характеристики досліджуваного діода Шотткі. Ми порівняли отримані результати для кожного контакту з результатами інших нещодавніх робіт у тієї ж галузі досліджень. Порівняння показало гарне узгодження з точки зору числових значень, а також ефективності запропонованого нами методу вимірювання.

**Ключові слова:** Провідність, Коефіцієнт ідеальності, Потенційний бар'єр, Послідовний опір, Діод Шотткі.