Compact model of a Schottky diode on GaN

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Abstract. In this paper, we consider the synthesis of a compact (SPICE) Schottky diode model on GaN. Synthesis of a compact (SPICE) Schottky diode model is implemented on the basis of a modified model of a conventional diode on a p-n junction by extracting the parameters contained in it from experimental data. To create the structures of the Schottky diodes, epitaxial structures of gallium nitride grown by the MOCVD method on a sapphire substrate were used. Ohmic contacts of diode structures were formed on ion-doped epitaxial layers. The result of the simulation of diode structures is the extraction from experimental data of parameters of the compact model of a Schottky diode on GaN.

1. Introduction
The search for wide-gap semiconductors, which could replace silicon, for creating various types of power devices, has been carried out for a long time. The strides achieved in recent years in the technology of nitrides of the III group make it possible to take a fresh look at this problem. Direct-gap semiconductor gallium nitride and solid solutions produced on its basis are promising materials for the creation of devices in various fields of electronics. The use of nitride structures is currently not limited to optoelectronic applications only. Such structures are used to develop the component base of power and microwave electronics, high-power microwave transistors and monolithic integrated circuits.

The variety of tasks for designing semiconductor devices has generated a whole range of circuit simulation systems. In modern circuit simulation systems, a special class of semiconductor device models known as SPICE models is used. They are universal nonlinear physical models, on the basis of which one can fairly easily go to any traditional system of parameters of models of semiconductor devices. Development of precision instrument models is an integral part of the modern semiconductor manufacturing industry. This is also due to the fact that instrument models are extremely important not only in the design and simulation of instrument operation, but are often used as a tool to optimize the production process [1].

2. Method of the experiment
The working structures of the Schottky diodes were formed on epitaxial structures of gallium nitride grown on 2-inch sapphire substrates by chemical vapor deposition using organometallic compounds (figure 1).
Ohmic contacts of diode structures were formed on n⁺ ion-doped layers. Si⁺ ion implantation was carried out on the Vesuvius-1 facility with an ion energy of 50 keV and a dose of \(10^{15}\) cm\(^{-2}\). To prevent the channeling effect, the plates are arranged at an angle of 7° to the normal of the incident beam. To activate the impurity introduced, photon annealing at a temperature of 1250 °C in a nitrogen atmosphere was used. SiO\(_2\) films were used as protective coatings during annealing [2].

The system Ti/Al/Ni/Au with the corresponding thicknesses of 50/4000/20/150 nm was chosen as the metallization for creating ohmic contacts. Schottky contacts with an area of \(9\times10^{-4}\) cm\(^2\) were formed on the basis of the Ni/Au two-layer metallization system and had thicknesses of 20 nm and 150 nm, respectively [3].

As a tool used for debugging and optimization of the technological process of manufacturing a Schottky diode, in this work, along with traditional techniques, the use of its compact model is proposed.

Synthesis of a compact (SPICE) Schottky diode model is implemented on the basis of a modified model of a conventional diode on a p-n junction by extracting the parameters included in its structure from experimental data: current-voltage characteristics, voltage characteristics and temperature dependences of the Schottky diode current.

**Figure 1.** GaN epitaxial structures: a – initial epitaxial structure; b – diode structure with ion-doped n-layer.

**Figure 2.** The equivalent Schottky diode circuits: a – a complete diode model; b – a diode model for the calculation of static parameters in live connection; c – model of the diode for calculating static parameters in the reverse inclusion.
For the extraction of the parameters of the compact model, a complex of algorithms was developed based on two types of numerical methods: a polynomial least squares approximation and a technique based on the mathematical apparatus of optimization theory. The software implementation of the algorithms is performed using the programming language MATLAB.

An additional advantage of this approach is the possibility of extracting a number of electrophysical parameters: the height of the Schottky barrier, the concentration of impurities in the substrate, the density of surface states at the metal-semiconductor interface, Richardson constant, the voltage drop for forward bias, and the current density at which the diode starts to self-heat. All of these parameters are extremely important in terms of assessing the quality of the technological process of manufacturing a diode [4].

3. Measurement results

For the direct branch of volt-ampere characteristic the parallel leakage resistance can be neglected, which corresponds to the equivalent circuit shown in figure 2b. This branch of volt-ampere characteristic is used to estimate the values of the static parameters of the diode, such as saturation current (Is), base resistance (Rs) and non-ideality coefficient (n).

In the region of small forward bias values (in the range of 0.1–0.3 V), the influence of the series resistance Rs can be neglected. Thus, the static parameters of the diode n and Is can be extracted from a part of the experimental data after an appropriate approximation.

The real Schottky diode, along with the space charge region, also contains a quasi neutral region, which, in combination with the contact resistance, is modeled by the resistance Rs. This resistance begins to affect the characteristics of the diode in the region of higher current values, reducing the effective voltage drop across the space charge region of the Schottky diode. When extracting from the experimental data of the parameter Rs, the functions that make up the MATLAB computer math toolkit are used. For this purpose, the objective function was formed with the previously found values of n and Is substituted into it and the required parameter was extracted. Comparison of experimental data with model representations (Figure 3) shows good conformity. It can be seen from Figure 3 that the greatest discrepancy for the two curves is observed in the voltage range of 0.5–2 V. This is probably due to the fact that in this voltage range, the nonideality coefficient is a function of the applied voltage, which is due to the increasing role of the field transfer mechanism charge carriers with increasing voltage.

Figure 3. Comparison of the experimental direct branch of volt-ampere characteristic with the model one with the extracted parameters Is = 5.96×10⁻⁷ A, n = 2.759, Rs = 103.5 Ohm.

For the reverse branch of volt-ampere characteristic (VAC), the dominant contribution to the volt-ampere characteristic on the initial part is made by leakage resistance; therefore, the equivalent circuit takes the form shown in figure 2c.
Figure 4. Comparison of the experimental reverse branch of volt-ampere characteristic with the model with the extracted parameter $R_p=5.599 \times 10^5$ Ohm.

Analysis of the volt-ampere characteristics given above indicates that in the voltage range (0 – 4) V the diode is shunted by leakage resistance, which is confirmed by Figure 4, which shows a fragment of the initial part of the experimental reverse branch of VAC. In this section of the VAC, the reverse saturation current of the diode is masked by the leakage current, the components of which are the surface leakage current and leakage currents of a dislocation nature. To estimate the magnitude of this resistance, an approximation of the initial part of the VAC by a straight line was performed. As in the case of extraction of the parameters $I_s$ and $n$ for the direct branch of the VAC, we use a polynomial approximation, which is part of the toolkit of the computer mathematics system MATLAB.

Analysis of the behavior of the reverse branch of the VAC for voltages in excess of 4 V (Figure 5) shows that a change in voltage within two orders of magnitude (95 V) leads to an increase in current by four orders of magnitude. This indicates a nonlinear dependence of the current on the voltage, which may be due to the influence of a complex of reasons, including the thermal emission current, the generation-recombination current of the depleted region, and the thermal field (tunneling) current. Identifying the role of each of these components is an independent task that requires additional research. However, from a formal point of view, the presence of this site on the reverse branch of the VAC can be modeled by introducing an additional nonlinear resistance into the equivalent circuit, which will require abandoning the standard diode model and proceeding to the synthesis of its macro model.

Figure 5. Current density versus voltage for reverse branch of volt-ampere characteristic.
One of the main parameters of diodes designed for power electronics is the breakdown voltage $V_B$, to which two parameters are assigned to the compact model: the breakdown voltage $V_B$ itself and the current $I_{BV}$ at which a breakdown is observed.

When analyzing the results presented in figure 5, we use the criterion for estimating the value of the breakdown voltage. It corresponds to the value of current density equal to 1 A cm$^{-2}$. Because the breakdown criterion is not achieved in the experimental data, it is necessary to approximate the final section of the experimental data to the breakdown voltage, and we get $B_V = 1092$ В and $I_{BV} = 8 \times 10^{-5}$ А.

To extract parameters such as barrier capacitance ($C_{JO}$), barrier height ($V_J$) and coefficient ($M$) depending on the type of dopant profile, it is necessary to simulate the dynamic mode of the Schottky diode during switching, for example, from one static mode to another. In this case, for the extraction of the corresponding parameters ($C_{JO}$, $V_J$, $M$), the results of measurements of the voltage characteristics of the diode are used.

Figure 6. Comparison of the experimental VAC with the model with extracted parameters $C_{JO} = 7.484$ пF, $V_J = 1.027$ В AND $M = 0.319$.

### 4. Conclusion

The basic parameters of the compact Schottky diode were extracted. The advantage of this approach is the possibility of extracting a number of electrophysical parameters: the height of the Schottky barrier, the concentration of impurities in the substrate, the density of surface states at the metal-semiconductor interface, Richardson constant, the voltage drop for direct bias, and the current density at which the diode self-heats up. The extracted high values of the resistance of the quasi neutral region, which is also associated with ohmic contacts, indicate the imperfection of their formation. Low values of resistance shunting the Schottky barrier may be due to the increased density of dislocations.

As a result, a set of parameters derived from the experimental data of the SPICE model of the Schottky diode on GaN was obtained, which is summarized in table 1.

| $n$ | $R_s$, Ohms | $B_V$, B | $I_{BV}$, A | $I_S$, A | $C_{JO}$, nФ | $V_J$, B | $M$ |
|-----|------------|---------|-------------|---------|--------------|---------|-----|
| 1.25 | 9.173 | 1092 | $8 \times 10^{-5}$ | $821 \times 10^9$ | 7.484 | 1.02 | 0.319 |
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