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Microwave Schottky diodes based on single GaN nanowires

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A series of Schottky diodes based on single GaN nanowires has been fabricated. Based on the data of small-signal frequency analysis (parameter S_{21}) of diode structures at various bias voltages, the parameters of the corresponding equivalent electrical circuit were determined. It is shown that the cutoff frequency of the fabricated diodes reaches 27.5 GHz.

Keywords: GaN, nanowires, microwave band, Schottky diode.

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Today, silicon electronics in the field of power and microwave devices has practically reached its fundamental capabilities, determined by the physical parameters of this material [1]. This stimulates the search for a new material base that covers the continuously growing requirements for modern semiconductor components.

Gallium nitride (GaN) is one of the promising materials for electronics due to the presence of a number of important properties: a wide bandgap, electrical, thermal, chemical and radiation stability. However, despite the commercial availability of a number of GaN-based components, its active implementation and serial production for civil use is currently limited by economic factors. The cost of planar GaN technology is high due to the need to use expensive growth substrates and, more importantly, the need to form buffer layers to compensate for the GaN lattice mismatch with the substrate material. Note that high-quality GaN substrates are very expensive and not widely available. Even when using silicon substrates, due to technological difficulties, primarily due to the large lattice mismatch between GaN and Si (at the level of 17%), the final cost of such products remains very high.

The limitations associated with the parameters mismatch of the crystal lattices of GaN and Si can be overcome in the transition from planar layers to arrays of nanowires (NWs). Due to their geometry, NWs have a number of unique properties and advantages. The synthesized NWs have excellent crystalline quality [2]. The mechanical stresses arising in NWs during growth effectively relax on the lateral surface; therefore, they practically do not have defects even in the case of synthesis on substrates with a significant lattice mismatch [3]. Commercially, GaN-based components usually consist of multilayer epitaxial structures, while NWs of high crystalline quality can be synthesized without the use of buffer layers. Moreover, the submicron transverse dimensions of NWs (usually about 100–200 nm) determine the ultra-low capacitance of a semiconductor device, which is important for ensuring high-speed operation.

One of the key elements of microwave electronics is the Schottky diode. Due to the fact that in such diodes there is practically no injection of minority carriers, there is also no corresponding diffusion capacitance. Therefore, they, as a rule, are distinguished by increased speed compared to on p–n-junction diodes. Schottky diodes are used in devices of various purposes, especially receivers and mixers of microwave frequencies.

The literature contains papers related to the study of the static characteristics of Schottky diodes based on GaN NWs (see, for example, [4,5]). The papers [6,7] study the dynamic characteristics of structures based on single or several GaN NWs, but their frequency capabilities are not presented.

This paper relates to the fabrication of Schottky diodes based on single GaN NWs, as well as to the study of their static and dynamic characteristics.

GaN NWs were synthesized by molecular-beam epitaxy on silicon substrates by analogy with [8]. Forced doping during NW growth was not carried out, while the background doping level is about $10^{17}\,cm^{-3}$ (electronic type of conductivity) [8]. The design of diode structures in this study involves the NWs separation from the growth substrate with subsequent transfer to an auxiliary non-conducting carrier substrate of quartz, as well as the formation of electrical contacts to them. To separate NWs, a part of the growth sample was placed in a flask with isopropyl alcohol, followed by treatment in an ultrasonic bath. Then, using a micropipette a suspension with NWs

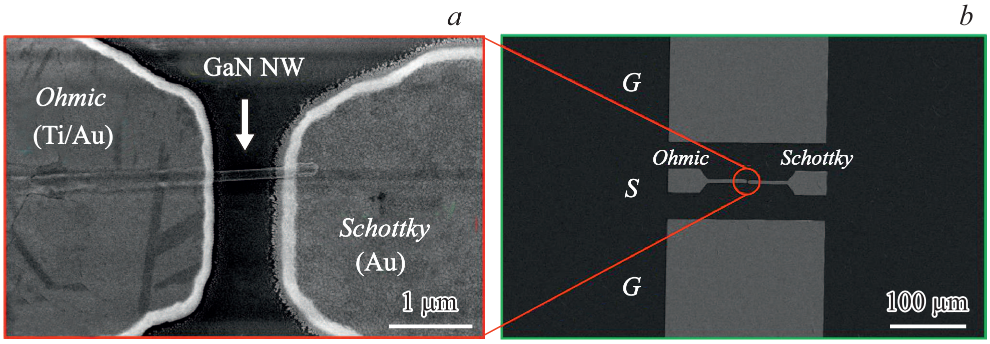

Figure 1. Typical SEM image of the fabricated diode structure in micro (*a*) and macroscale (*b*).

was deposited on a quartz wafer and dried under a nitrogen flow. The contact pads were made in *GSG*-configuration (ground–signal–ground) [9], which is necessary to carry out the corresponding microwave studies. To form metal contacts photolithography, deposition of metal layers, and the procedure of explosive removal (lift-off) of photoresist residues were carried out. In this case, at the first stage Ti/Au metallization of *G*-pads and ohmic contacts (Ti/Au) to one ends of the GaN NWs were formed, and at the second stage the Au-based Schottky barrier contacts to the other ends of the NWs were formed. Fig. 1, *a*, *b* shows typical images of the diode structure obtained by scanning electron microscopy (SEM). In total, in the framework of this paper, eight diode structures were studied. Next, the analysis of the data obtained for the diode that demonstrated the best frequency characteristics will be presented.

Fig. 2, *a* shows a schematic representation of the experimental set-up for estimating the frequency properties of diodes based on GaN NWs. With the help of a Keysight Technologies N5234B vector network analyzer (VNA), the analysis of *S*-parameters (scattering matrix of a multiport device [10]) was carried out in the frequency range 0.1–40 GHz. The diodes were connected to a vector network analyzer in a two-port circuit using probes. A Keithley 2401 source-meter was used as a voltage source. The bias voltage was applied to the diodes under study using SHF BT 45R mixers. Port 1 ($P1$) served as the source of the signal, and port 2 ($P2$) served as the receiver.

Fig. 2, *c* shows the measured current-voltage (IV) characteristic of the diode based on the single GaN NW (see the SEM image in Fig. 1, *a*, NW diameter 160 nm, gap between contacts 1 μm). The diode exhibits characteristic rectification with threshold voltage of 1 V. The voltage polarity corresponding to the diode ON-state corresponds to the electronic type of NW conduction. The diode characteristics will largely depend on their series resistance, which in turn, in the case of NWs, depends on their geometric parameters (diameter, length of NWs between contacts). To determine the series resistance of NWs within a diode structure, it is necessary to apply a significant forward bias, which can lead to the diode degradation. Nevertheless, for further research we can limit ourselves to differential resistance, which for this structure is 76 kΩ (for +3 V bias).

For a more detailed analysis of the dependences obtained, as well as for estimating the cutoff frequency of the diode we considered the equivalent circuit of the structures under study (Fig. 2, *b*). Here R_j and R_s correspond to the Schottky barrier resistance and NW series resistance, C_j — Schottky barrier capacitance, C_{cont} — capacitance of contact pads (between *S*- and *G*-strips), and C_p — shunt parasitic capacitance due to the gap between signal pads. In the present paper we did not optimize the topology of contact pads to match the characteristic impedance of the transmission line (50 Ω). However, the results of a small-signal frequency analysis of the contact pads revealed the absence of significant losses for the microwave signal transmission in the frequency range under consideration (i. e., the capacitance C_{cont} of the contact pads can be neglected in this case).

Fig. 2, *d* presents the results of small-signal frequency analysis in the form of parameter $S_{21}(f)$ for one of the diodes based on a single GaN NW at various bias voltages. In the frequency range under consideration, the $S_{21}(f)$ curves take the form typical for resistive-capacitive load. In this case, the resistive component begins to manifest itself at frequencies below 10 GHz as the forward bias of the structure increases, when the resistance of the Schottky barrier abruptly decreases. In the range 0.1–0.4 GHz, for relatively high forward bias voltages, the parameter S_{21} is practically independent of frequency, which corresponds to the ON-state diode mode, and the signal propagates predominantly through the NW. For such a mode, it is possible to estimate the differential resistance of the diode $(R_s + R_j)$, which at forward bias voltage +3 V reaches 71 kΩ, which is in good agreement with data obtained from the IV data.

At frequencies above 10 GHz, the forward bias value has practically no effect on the shape of the $S_{21}(f)$ curve, which is caused by the already prevailing contribution of the shunting parasitic capacitance of the gap between the contact pads (C_p) at the microwave signal through the diode. The diode cutoff frequency f_{cutoff} can be calculated

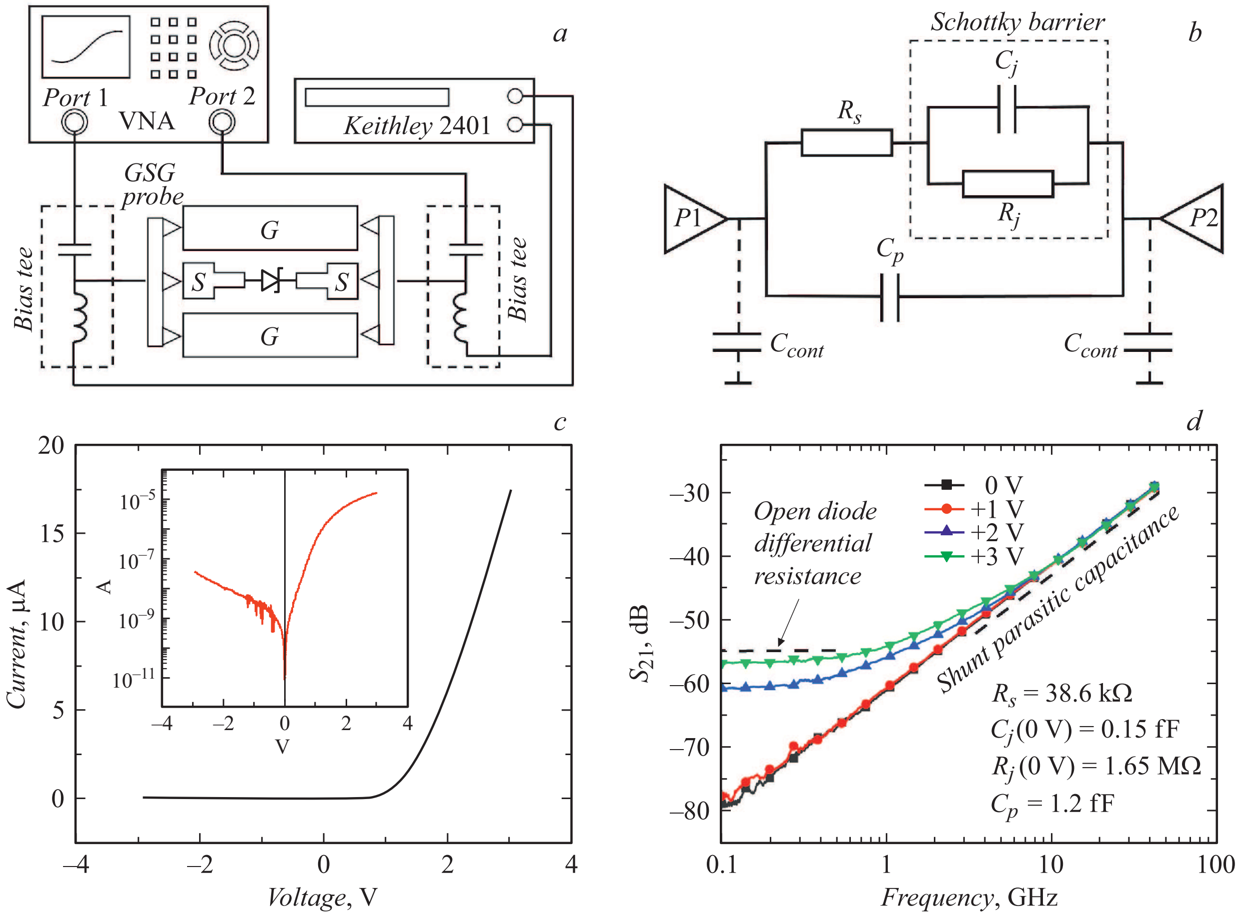

Figure 2. Schematic representation of the experimental set-up (*a*), the proposed equivalent circuit of the studied diode structures (*b*), IV curves (*c*) and S_{21} curves at various bias voltages (*d*) of a diode based on GaN NWs.

according to the following formula [11]:

$$f_{cutoff} = \frac{1}{2\pi R_s C_j}. \quad (1)$$

The parameters R_s and C_j were estimated by approximating the experimental dependences S_{21} by an analytical expression of the following form:

$$S_{21} = \frac{2Z_0}{Z + Z_0}, \qquad Z = (R_s + R_j||C_j)||C_p. \quad (2)$$

Here Z is the impedance of the equivalent circuit, and Z_0 is the characteristic impedance of the transmission line of the microwave signal (in this case 50 Ω). The parameters R_j and C_p also varied. Fig. 2, *d* shows the obtained values of the parameters of the equivalent circuit for the considered diode. The cutoff frequency in this case reaches 27.5 GHz, which lies in the frequency range of satellite communication systems, as well as 5G [12] networks. Also note that the barrier capacitance turns out to be by several times smaller than the shunting parasitic capacitance of the contact pads, which requires the geometry optimization of the structure.

Finally, samples of Schottky diodes based on single GaN NWs were fabricated. The current-voltage characteristics of diodes were investigated. The frequency dependences of the S_{21} parameter are studied by small-signal frequency analysis in a wide frequency range. The experimental data are approximated within the proposed equivalent circuit of the diode based on GaN NWs. The analysis of the obtained data for the diode, which demonstrated the best frequency characteristics, showed that the cutoff frequency is 27.5 GHz. To further improve the diodes, it is necessary to carry out a thorough optimization of the structure design.

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Conflict of interest

The authors declare that they have no conflict of interest.

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