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Improvements in the performance of the n^+ cap-layer GaN in the formation of transistor structures based on AlGaN / GaN

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Abstract. The use of heavily doped protective layers of gallium nitride in AlGaN/GaN heterostructures makes it possible to improve the characteristics of transistors. In this paper, using structures with a protective cap layer and the process of selective etching, structures of HEMT transistors are fabricated. Using the n^+-GaN layer, remove the contact resistance from 1 Ω·mm to 0.74 Ω·mm. The transistors show a maximum drain current of 380mA/mm and a steepness of 140mS/mm with an output power of 5W/mm.

1. Introduction

Highly efficient gallium nitride transistors are successfully used in microwave power devices and circuits, thanks to a unique combination of semiconductor material properties, namely, a large band gap, a high electric breakdown voltage and a high saturation speed of carriers.

When developing instrument structures, the correct choice of the parameters of the initial material largely determines the achievement of the ultimate characteristics of the finished device. To obtain the ultimate characteristics of AlGaN / GaN-based transistor structures, it is important to use protective layers that can act as thin dielectric films (Si_3N_4, SiO_2, Al_2O_3) or thin semiconductor layers of gallium nitride (doped or undoped). However, due to the low mobility and wide bandgap of undoped AlGaN layers, conventional approaches to using AlGaN as a surface protective layer limit the performance of devices, especially for microwave power applications. To reduce the contact resistance, unalloyed or slightly doped thin GaN layers are introduced, while the characteristics of the devices are not improved because of the increase in the distance from the gate to the channel and the reduction of the induced piezoelectric charges. Therefore, the addition of a heavily doped n + -GaN layer over the traditional HEMT structure of AlGaN / GaN can improve instrument performance. At the same time, this doped layer must be removed before the formation of Schottky gate metallization to reduce the leakage current of the gate.

2. Instrument structure of AlGaN / GaN

The structures used in the work were grown on sapphire substrates by the method of chemical deposition from the gas phase using organometallic compounds (MOCVD). The structure of the layers is shown in Figure 1. The mobility and concentration of charge carriers in the structure with the n + layer were 1820 cm^2 / V · s and 1.04 × 1013 cm^{-2}. For structures without a protective layer, these parameters were 1675 cm^2 / V · s and 1.21 × 1013 $cm^{-2.}$ The decrease in carrier concentration is caused by the reverse direction of the piezoelectric polarization between the n + -GaN layer and the AlGaN barrier layer, where piezoelectric charges are the main charge carriers in the HEMT AlGaN-GaN [1]. In this case, a decrease in the concentration of sheet carriers always leads to a higher mobility of a two-dimensional electron gas. After removing the protective layer under the gate metallization, the reverse direction of the piezoelectric effect can be neglected.

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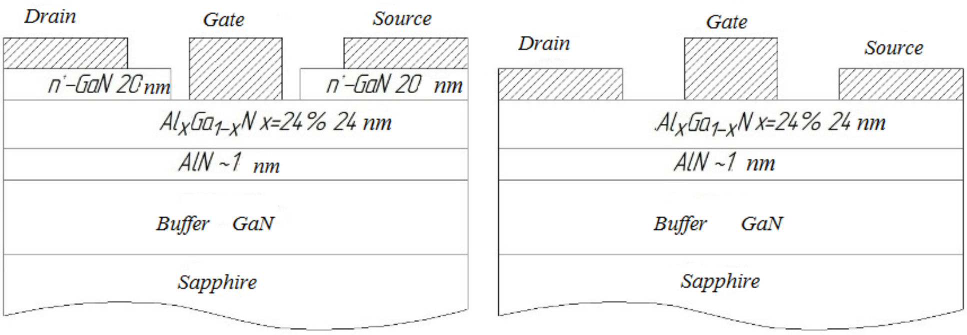

Figure 1. The cross section of the structures used in the work.

3. Manufacturing technology of instrument structures

The fabrication of instrument structures began with the formation of mesa-isolation. Under the formation of mesic, it is meant to create a structure on a heteroepitaxial plate with conductive (active) and nonconducting layers by etching the heterostructure surface. The purpose of the operation is to separate the active regions on which the devices are formed from each other in order to avoid electrical contact between the instruments. The limitations of liquid etching methods for nitride semiconductors lead to the need to introduce plasma etching techniques. The most effective at present is the technology of nitride semiconductors etching in plasma using sources on an inductive high-frequency discharge. Such sources allow to create a denser plasma with high uniformity and controllability. In this work, etching in a mixture of $Cl_2/BCl_3/Ar$ using inductively coupled plasma (ICP) at a rate of 800 nm / min was used to form the mesa-isolation [2].

The ohmic contacts of the drain and the source were formed with the help of an explosive photolithography process using a two-layer photoresist system LOR 10A and S1813. The use of a two-layer system based on LOR resist (Figure 2) allows to form a negative slope of the walls, facilitating the process of metallization removal and providing an even edge of the contact pads. As the metallization of ohmic contacts, a Ti /Al/Ni/Au system was used, formed by electron beam deposition. The annealing of the metallization was carried out at a temperature of 820 °C for 30 seconds under a nitrogen atmosphere.

The contact resistance was evaluated by the long-line method [3] with a set of square contact pads 100 × 100 μm at a distance of 5, 10, 15, 20, 25 and 30 μm. The calculation of the contact resistance gives a value at the level of 0.8 Ohm · mm for a structure with n^+-GaN protective layer and about 1.0 Ω · mm for structures without a protective layer.

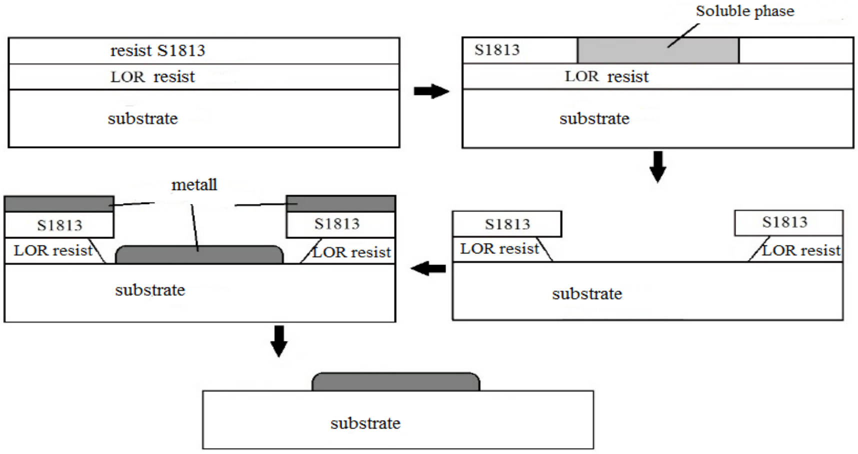

Figure 2. Stages of forming a resistive mask for "Explosive" photolithography.

Measurements of the resistance versus distance by the long-line method and the current-voltage characteristics of contacts with a distance of 30 μm for the structures under consideration are shown in Figures 3 and 4.

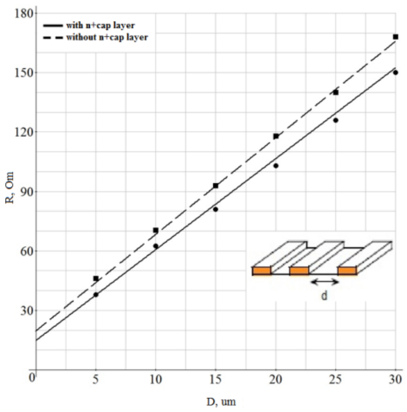

Figure 3. Dependence of the resistance on the distance between the pads. The inset shows a fragment of the test structure.

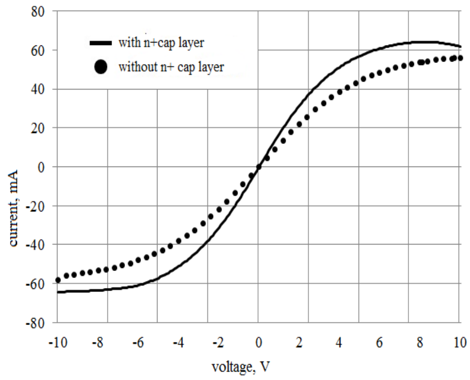

Figure 4. Volt-ampere characteristics of drain-source on different structures.

Before barrier metallization formation, it is necessary to remove the conductive cap layer of GaN. To carry out this operation, a process of selective etching of GaN with respect to AlGaN was developed, at which a sharp decrease in velocity occurs when the AlGaN layer is reached. Such a process is realized by adding an oxygen additive to the chlorine-containing mixture Cl_2/Ar, which, reacting with aluminum, forms an Al_2O_3 compound, which limits further etching. At the same time, the selectivity of GaN/AlGaN etching is determined not only by the amount of oxygen, but also by a number of parameters. This is the power of the inductively-coupled plasma source, high-frequency power and pressure in the chamber. As a result of the work, the optimum etching regimes were determined from the point of view of obtaining the required etching rate of gallium nitride and the selectivity. The dependence of GaN and AlGaN etching rate and etching selectivity on these parameters is shown in Figure 5.

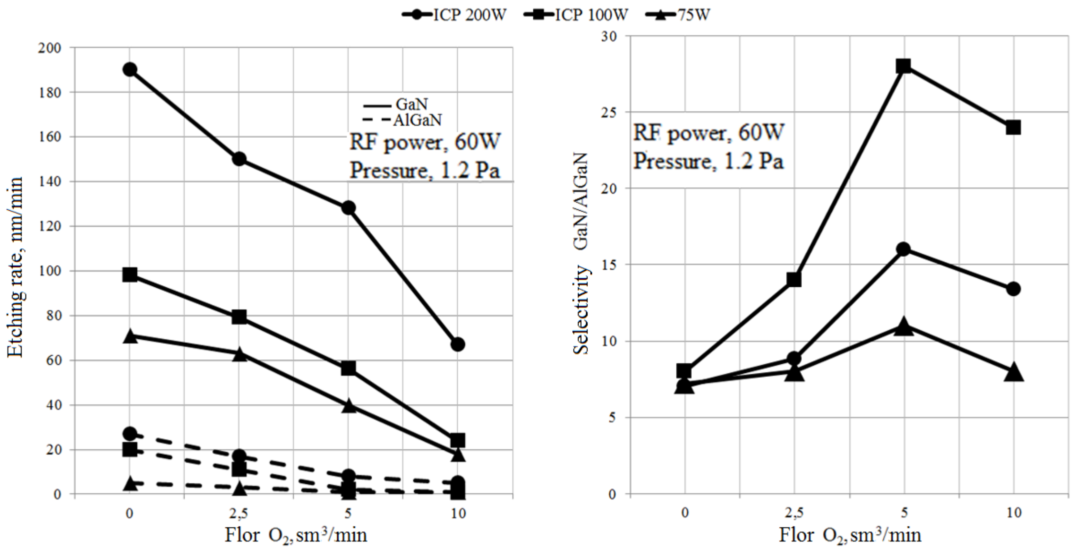

Figure 5. Dependence of the rate and selectivity of etching on regimes.

In accordance with the presented dependences, the etching mode was chosen: $Cl_2/Ar/O_2$ 60/10/10 cm^3/min: ISP power – 200W, RF power – 30W and pressure - 1.2Pa, permitting etching selectivity about 30:1.

After removal of the n^+-GaN layer, barrier metallization was formed. The gates of transistor structures with a length of 1.0 µm and a width of 100µm were manufactured by successively performing electron-beam deposition of the Ni/Au system and explosive photolithography.

After the formation of the transistor structure contact systems, the devices were passivated by a Si_3N_4 film obtained by plasma-chemical deposition at a temperature of 250 °C. The dielectric film provides stabilization of the surface of the instrument structure.

4. Volt-ampere and voltage-voltage characteristics of transistor structures

As a result of the technological process, models of transistor structures were obtained. The study of characteristics began with the determination of the parameters of barrier metallization using the test structures of Schottky diodes. The height of the barrier and the nonideality coefficient calculated from the current-voltage characteristics of Schottky test diodes were determined. The results of the calculation are given in Table 1.

Table 1 – Calculation of barrier metallization

	Coefficient of nonideality	Barrier height, eV
n^+-layer	0.62	1.77
without n^+-layer	0.66	1.73

The close values of the barrier metallization parameters show that the developed process of selective etching does not introduce significant defects into the barrier layer of AlGaN.

The current-voltage and transient characteristics of the fabricated structures are shown in Figures 6 and 7.

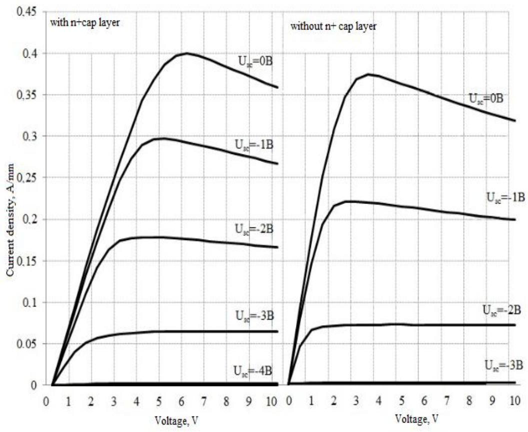

Figure 6. Output volt-ampere characteristics of transistor structures.

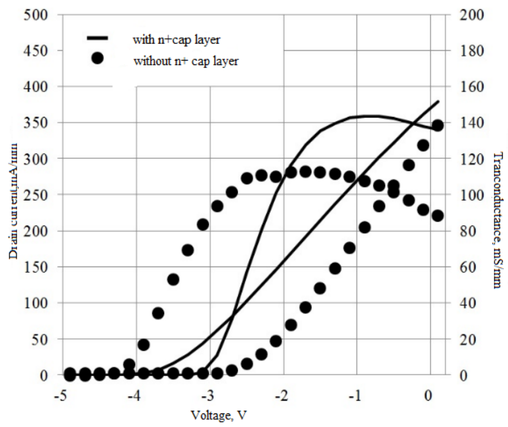

Figure 7. Transient characteristics of transistor structures.

Note that the addition of a conductive layer provides a low resistivity of the conductive channel. This leads to a low threshold voltage, greater steepness and current density. For structures with n^+-GaN layer, the maximum steepness and current density were 380 mA/mm and 143 mS/mm, while for structures without a protective layer they were 345 mA/mm and 112 mS /mm.

Another important parameter of transistors is the size of the gate-drain capacitance. The capacitance value has a key influence on the frequency characteristics of transistors. Dependencies of the gate-drain capacitance on the gate voltage for the structures under consideration are shown in Figure 8. At a gate voltage of 0 V, the capacitance values are 0.66 pF for structures with a protective layer and 1.12 pF for structures without an n^+-layer.

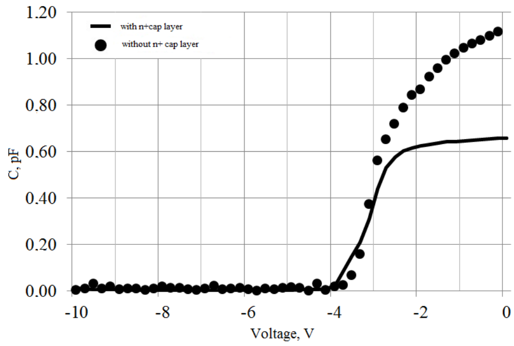

Figure 8. Gate-source capacitance voltage on the gate.

5. Conclusion

In this paper the characteristics of transistor structures with a protective heavily doped layer of gallium nitride and without it were compared. Improved performance is shown when using the n^+-layer due to the reduction of contact resistance and channel resistance. The current density is 380mA/mm, the steepness is 143mS/mm and the output power density is 5W/mm.

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