A fabrication of AlGaN / AlN / GaN HEMT without annealing of ohmic contacts

I A Rogachev¹, O I Meshkov¹, A F Tsatsylnikov², V V Lyndin², E E Zavarin², D A Vakina¹, A S Kurochka¹ and A N Ganin¹

¹ JSC "RPC "Istok" named after Shokin", 2A, Vokzalnaya Str., Fryazino, Moscow Region 141190, Russia
² Submicron Heterostructures for Microelectronics, Research & Engineering Center, RAS, 26, Politekhnicheskaya street, Saint Petersburg, 194021, Russian Federation.

E-mail: ilya_rogachev_89@mail.ru

Abstract. The article discusses the technology of creating a transistor using selectively-grown non-annealed ohmic contacts. As a result, a transistor was obtained, with a gate length of 1 μm. An output power density of 3.25 W / mm, an efficiency of 47% and a gain of 11 dB at a frequency of 3 GHz.

1. Introduction

On the modern market of high-power microwave electronics, gallium nitride has already taken up a strong position and has found its application in a number of industries, in the production of satellite communications systems, radar stations, wireless electronics, etc., displaces similar instruments created using similar silicon and gallium arsenide devices. [1, 2]. Much of the production of devices on gallium nitride is focused on military applications.

The main advantage of gallium nitride over other common electronics materials is a wide band gap - 3.5 eV versus 1.1 eV for silicon and 1.4 for gallium arsenide. This means that GaN transistors will operate at higher temperatures and are less sensitive to ionizing radiation (this is important for space and special electronics). In theory, the operating temperature of GaN devices reaches 500 °C, but in practice it still amounts to 150–200 °C. The maximum electric field strength in GaN - 3.3 106 V / cm - is 11 times more than that of silicon. And due to the high density of charge carriers, GaN transistors withstand much higher currents.
Figure 1. Characteristics of semiconductor materials.

The diagram (figure 1) considers five key characteristics: high dielectric strength, high operating temperature, high current density, high switching speed and low resistance. It can be seen that gallium nitride benefits from traditional materials in all basic characteristics [3].

One of the problems of creating a transistor on AlGaN / GaN heterostructures is the problem of creating high-quality ohmic contact. When using the traditional method, it is necessary to apply high-temperature (800-950°C) rapid thermal annealing, which leads to problems combining the topology of different layers, complicating the technology of creation, deterioration of the topology and geometry of ohmic contacts and labels. These problems can be avoided by applying the method of selective growth of epitaxial structures in the areas of the formation of ohmic contacts. On the one hand, several additional technological operations are introduced into the technological route, and on the other hand, this will lead to an improvement in the quality of the ohmic contact and a decrease in the specific resistance. The absence of high-temperature rapid thermal annealing ensures the preservation of the quality of the morphology and geometry of the ohmic contact, which will lead to an increase in the percentage of yield of devices on the wafers and simplify the subsequent processes of photo- and electronic lithography.

2. Experiment

AlGaN / AlN / GaN heteroepitaxial structures were used as the starting material (figure 2) on a sapphire substrate, the structures were grown at the enterprise “STC-Microelectronics RAS”. The main characteristics of the original semiconductor structures: carrier mobility in the channel is $1200 \text{ cm}^2 / \text{V} \cdot \text{s}$, the carrier concentration in the channel is $1.2 \cdot 10^{13} \text{ cm}^{-2}$ and the layer resistance is $320 \pm 3.8\% \Omega / \text{sq}$.

![Figure 2. Schematic representation of the epitaxial heterostructure.](image)

Si$_3$N$_4$ 5 nm
AlGaN, 17 nm, X(Al)=0.31
AlN 0.7 nm
GaN 2500 nm
sapphire (0001) 0.43 nm
Initially, 4 variants of growing selective ohmic contacts were used (figure 3). An insity dielectric layer with thicknesses of 5 and 100 nm was grown on the surface of these wafer. On wafer with a thick dielectric (100 nm), it was supposed to grow selectively epitaxial layers directly on the surface of the wafer, without going into the semiconductor. On wafer with a thin dielectric (5 nm), it was necessary to make recesses according to the topology of ohmic contacts, so that the bottom of the groove was below the level of formation of a two-dimensional electron gas, and then selectively grow high doped epitaxial layers (~ 10^{18-19}).

The contact and active layers of gallium nitride were etched through an SPR-700 photoresistive mask and a Si3N4 protective mask in an inductively coupled plasma in a BCl3 / Cl2 gas mixture for 95 s in the “Corial 200IL” unit to a depth of 100 nm.

Growing doped epitaxial structures of GaN ohmic contacts "Dragon" was performed using the MOCVD method.

With the selective growth of epitaxial structures by the MOCVD method, a large number of defects appear on small areas on the surface of heavily doped layers, which adversely affects the parameters of the finished device. In the case of growth over large areas, such defects are absent. Therefore, the growth topology of selective epitaxial growth was optimized in order to reduce the number of growth surface defects. Selective growth of epitaxial structures was carried out over the entire surface of the wafer, with the exception of areas of gate formation (2x125 μm).

**Figure 3.** The scheme of options for selective growth of high doped epitaxial structures: a - selective growth of GaN without recess (Si3N4 - 100 nm.); b - selective growth of AlGaN without recess (Si3N4 - 100 nm.); c selective growth of GaN with recess of 100 nm. (Si3N4 - 5 nm.); g - selective growth of AlGaN with recess of 100 nm. (Si3N4 - 5 nm.).

**Figure 4.** Scheme of the selective growth of doped GaN epitaxial structures: a is the initial topology; b - optimized topology.

Mesa isolation was formed using plasma-chemical etching in inductively coupled plasma in a mixture of gases Cl2 + BCl3. For the formation of ohmic contacts, traditional metallization was used: Ti / Al / Ni / Au, deposited by vacuum thermal evaporation. The gate was formed using photolithography (gate length 1 μm), followed by deposition of Ni / Au. Upper metallization was created through the use of air bridges.

**3. Result and discussing**

At the first stage of work, a study was conducted on the choice of material for selective growth (GaN or AlGaN) and the effect of the recession in the areas of selective growth of epitaxial structures was determined. In the second stage, an optimized selective growth topology was tested.
An analysis of the experimental results showed that the minimum resistivity of ohmic contacts is obtained by selective epitaxial growth of highly doped gallium nitride in areas etched (with a recession) below the level of formation of a two-dimensional electron gas (figure 5.).

At the second stage of the study, an optimized topology of selective growth of gallium nitride epitaxial layers with depressions was applied (figure 4), a gate and air bridges were formed, and then the electrical parameters of the instrument were measured.

After the formation of a gate with a length of 1 μm, the characteristics of the transistor are obtained (table 1). Next, air bridges were formed and a powerful transistor was obtained (figure 6).

**Figure 5.** CVC of ohmic contacts for various variants of selective growth.

**Table 1.** Transistor characteristics

| Before annealing the gates | After annealing the gates |
|---------------------------|--------------------------|
| Voltage | Current Density | Voltage | Current Density |
| 0 | 0.35 A/mm | 0 | 0.33 A/mm |
| 1 | 120 mS/mm | 1 | 125 mS/mm |
| 2 | 4 | 2 | 10 |
| 3 | 0.7 V (not clear) | 3 | 0.7 V (clear) |
| 4 | Leakage currents - more than 50 μA at a voltage of 16 V | 4 | Leakage currents - 30 μA at a voltage of 16 V |
At the final stage, measurements of the electrical device obtained were carried out. At a frequency of 3 GHz, we obtained the following dependences of the output power on the input power (figure 7(a)), the efficiency on the input power (figure 7), and the gain on the input power (figure 7(c)). The measurements were carried out on a sample with a 1 mm periphery.

At a frequency of 5 GHz, we obtained the following dependences of the output power, the efficiency, gain factor on the input power (figure 7 (d-f)).

### Table 2. LOAD-PULL measurements.

| Mode       | Pout max, mW | Pin, dbm | AE, % | p.gain, dB |
|------------|--------------|----------|-------|------------|
| -2.9_12V_3G | 989.9        | 21.66    | 1.63  | 8,292      |
| -2.9_18V_3G | 1558         | 23.35    | 3.59  | 8,58       |
| -2.9_20V_3G | 1943         | 24.28    | 4.59  | 8,605      |
| -2.9_22V_3G | 1943         | 24.28    | 4.59  | 8,605      |
| -2.9_24V_3G | 2106         | 24.22    | 5.45  | 9,013      |
| -2.9_28V_3G | 2416         | 25.07    | 45.56 | 8,759      |
| -2.9_30V_3G | 2537         | 25.1     | 45.81 | 8,947      |
| -2.9_32V_3G | 2661         | 25.74    | 43.57 | 8,515      |
| -2.9_40V_3G | 3253         | 24.39    | 47.73 | 10,74      |
| -2.9_40V_5G | 2911         | 26.6     | 35.8  | 8,038      |

$P_{\text{in}}$ is the power absorbed by the sample.

$$P_{\text{in}} = \frac{1}{2} \cdot (|a_1|^2 - |b_1|^2)$$  \hspace{1cm} (1)

where $a$ and $b$ are the incident and reflected waves at the input ($a_1$, $b_1$) of the sample being measured;

$P_{\text{out}}$ is the output power absorbed by the load with an impedance installed at the output impedance transformer.

$$P_{\text{out}} = \frac{1}{2} \cdot (|a_2|^2 - |b_2|^2)$$  \hspace{1cm} (2)

where $a$ and $b$ are the incident and reflected waves at the output ($a_2$, $b_2$) of the sample being measured;

$PAE$ - coefficient of performance by added power.

$$PAE = \frac{P_{\text{out}} - P_{\text{in}}}{P_{\text{dc}}}$$  \hspace{1cm} (3)

$P_{\text{dc}}$ is the power consumed from the power supply.

$$P_{\text{dc}} = V_1 \cdot I_1 + V_2 \cdot I_2$$  \hspace{1cm} (4)

where $V_1$, $I_1$ are the voltage and current of positive polarity, and $V_2$, $I_2$ is of negative polarity;

$Operating \ Gain$ - functional gain.

$$K_p = \frac{P_{\text{out}}}{P_{\text{in}}}$$  \hspace{1cm} (5)
Figure 7. Dependence of output power (a, d), efficiency (b, e) and gain (c, f) on the input power. 3 GHz – (a-c). 5 GHz – (d-f).

4. Conclusion
As a result of the work, a transistor formed using the technology of non-annealing ohmic contacts with a gate length of 1 μm was obtained. As a result of measurements of the electrical parameters of the device at a frequency of 3 GHz and 5 GHz, with a supply voltage of 40 V. Due to the rather long gate length, the maximum values of the transistor parameters were obtained at a lower frequency (3 GHz).

References
[1] I Vikulov, Technological base of GaN high-frequency microelectronics: companies, processes, opportunities, 2017 Electronics: science, technology, business, №1 (00161) 106-115
[2] M V Kuliev, Overview of modern GaN transistors and development directions, 2017 Electronic equipment. Series 2. Semiconductor devices. 2 (245) 18-28;
[3] Van Daele, B. Van Daele, G. Van Tendeloo, W. Ruithooren 2005 J. Appl. Phys. Lett. 87 061905-1 - 061905-3