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Technology for forming micro devices based on gallium nitride

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Abstract. The technology of forming micro devices based on gallium nitride, including the main stages of manufacturing, namely, inter-assembly isolation, formation of non-straightening (ohmic) and straightening (Schottky barrier) contacts, surface passivation, formation of interelectric connections in the form of "air bridges", plate grinding, cutting plate into crystals and sorting out, is considered. A short technological cycle of manufacturing microstructures with a description of the main operations is given. As a result of this work, experimental samples of transistors with a gate length of 0.5 microns were obtained.

1. Introduction

Currently, much attention is paid to such wideband semiconductors as gallium nitride, silicon carbide and diamond as promising materials for the creation of effective devices for power and hightemperature electronics. The technology of devices based on gallium nitride is developing most intensively, thanks to its use for the production of LEDs. At the same time, a unique combination of physical properties, including a large band gap, a high drift velocity of electron saturation, high breakdown voltages, high thermal conductivity, and high chemical and thermal stability, makes it possible to consider nitride compounds not only in optoelectronics, but also for the development of a component base of power SHF electronics [1].

The system of solid solutions based on Al_xGa_{1-x}N, as a material for high-temperature, high-voltage, high-frequency and high-current applications, can significantly expand the operational capabilities of semiconductor technology. A unique combination of physical properties allows considering these materials to create a new generation of microelectronic devices. It is with the introduction of such materials that a breakthrough in SHF and high-current electronics is currently associated.

The aim of this work is to develop the basic technological operations of transistors formation based on the AlGaN/GaN structure in order to create a prototype and to study the characteristics of the obtained instrument structures.

2. Methods of Experiment

AlGaN/GaN heterostructures grown by the MOCVD method (chemical vapor deposition using organometallic compounds) on a 2-inch diameter sapphire substrate were used as the starting material for the development of the transistor manufacturing process. The mobility and concentration of charge



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carriers in the used heterostructures were 1650 cm²/V s and 1.27 $\times 10^{13}$ cm⁻². The structure of the source material is shown in figure 1.



Figure 1. Schematic cross-sectional view of AlGaN/GaN heterostructure.

For the formation of microstructures based on GaN, it is necessary to perform a number of technological operations. The determining operations that make the main contribution to the parameters of microstructures are the creation of reliable inter-instrument insulation and the formation of high-quality metal – semiconductor contacts.

2.1. The formation of inter-instrumental insulation of structures based on gallium nitride

For etching materials of group A³B⁵, both chemical ("liquid") and plasma ("dry") etching methods can be used. "Liquid" methods of material removal involve the use of liquid solutions for chemical etching of a semiconductor areas unprotected with mask. These methods are simple to implement and do not require sophisticated technological equipment. But when working with AlGaN/GaN heterostructures, the "liquid" method is not widely used, because due to the strong chemical bonding in nitride semiconductors it is difficult to choose solutions that allow the chemical etching of the material. GaN photostimulated electrochemical etching is reported; however, this method depends on many parameters and is poorly reproducible [2, 3]. Due to the limited possibilities of liquid etching of nitride semiconductors, the main efforts of the technologists were directed to the development of dry etching methods. To implement the dry etching method in this work, we used a plasma-chemical etching unit with an inductively coupled plasma (ICP) source.

Inter-instrument isolation in the form of a mesa structure is carried out by etching the heteroepitaxial structure below the level of a two-dimensional electron gas formed at the interface between the AlGaN and GaN layers.

The binding energy for GaN is 8.92 eV/atom; therefore, the etching conditions for this material are significantly different from silicon, gallium arsenide and indium phosphide, semiconductors with well-studied etching processes.

To form the mesa areas, etching modes of nitride layers in plasma based on the Cl₂/BCl₃/Ar gas mixture were developed. The development of etching processes consisted in the selection of modes that ensure a sufficiently wide range of etching rates required for various applications [3].

For the heterostructures considered in this work, the mesa areas were etched to a depth of about 200 nm, which ensured reliable inter-instrument isolation and the necessary relief for combining the topological pattern on the plate.

When choosing masking coatings, it is necessary that they have chemical resistance to an aggressive plasma gas atmosphere, have high adhesion to the substrate, and are easily removed after etching without changing the morphology of the semiconductor surface [4].

To carry out the etching process, a mask based on SP15 photoresist prepared for etching in a chlorine-containing medium was used. Such a mask provides reliable protection of the heterostructure, the absence of erosion of the edges of the mask and ease of removal after the etching process.

The structures were etched at an inductively coupled plasma source power of 600 W, a displacement of 100 W, a pressure of 1.2 Pa, and a gas flow ratio of $BCl_3/Cl_2/Ar$ equal to 20/60/10 cm³/min. The etching time was 25 seconds.

Thus, the formation of inter-instrument insulation requires the following sequence: photolithography of etching windows of a semiconductor, plasma-chemical etching of a semiconductor, removal of a photoresist mask and control of the depth of etching.

2.2. The formation of ohmic contacts to heterostructures based on gallium nitride

The next stage in the formation of the instrument structure is the formation of ohmic contacts to the heterostructure. Ohmic contacts must meet a number of requirements: low contact resistance, good adhesion of metals to the semiconductor, a flat edge of the contact boundary, resistance to electromigration, high thermal stability, preservation of morphology during heat treatment, good reproducibility.

To create an ohmic contact to nitride heterostructures, Ti-based multicomponent contacts are most often used, which during heat treatment form compounds with a low output work. The low resistance of the ohmic contact is usually associated with the formation of nitrogen vacancies due to the interaction of the semiconductor with the contact material, for example Ti.

Contacts are formed by explosive photolithography using a two-layer photoresist system that provides a negative slope of the wall profile to improve the "explosion" and remove metal. This is achieved by reversing the latent positive image. Figure 2 shows the main stages of contact formation.



Figure 2. Stages of forming a resistive mask by explosive photolithography.

In this work, the Ti/Al/Ni/Au system was used as metallization of ohmic contacts. Contacts were formed using explosive photolithography and electron beam metal sputtering.

After creating the contact pads, annealing was carried out at a temperature of 720 °C for 45 seconds. Contact resistance was measured with test elements using the long line method [5] at the Cascade Microtech semi-automatic station. The Agilent B1505A semiconductor performance meter

was used as a measuring part for monitoring parameters at a direct current. Current-voltage characteristics and the appearance of ohmic contacts are shown in figures 3 and 4.



Figure 3. Optical microscopy images of Ti/Al/Ni/Au on the AlGaN/GaN heterostructure.

Figure 4. The I-V characteristic for Ti/Al/Ti/Au to AlGaN/GaN before and after annealing at 720°C.

Calculation of specific contact resistance (ρ_c), performed by the long-line method, shows ρ_c at the level of 0.6 Ohm \cdot mm.

2.3. Formation of a straightening contact (Schottky barrier) to heterostructures based on gallium nitride

The SHF parameters of modern microwave transistors at heterojunctions are mainly determined by the gate parameters of circuits based on them. Obtaining MIS amplifiers for a certain frequency range is determined by the material of the semiconductor and the geometry of the gate.

The formation of a mushroom-shaped gate consists of the following key operations: electron beam lithography to obtain a profile of the future gate; application of barrier metallization; "explosion" of an electronic resist.

Let us consider the stage of formation of the mushroom-shaped profile in the resist.

After dehydration on the tile at a temperature of 120° C, a multilayer system of electronic resists with intermediate drying on the tile was applied to the plate by centrifugation (figure 5a, 5b). The system consists of layers PMMA950K/PMGI/Copolymer/PMGI/PMMA950K with a total thickness of about 1.3 μ m. The sequence of layers and their thicknesses were optimized for separate exposure and controlled manifestation of mushroom-shaped profiles.

The prepared plate is exposed in an electron beam exposure apparatus. The upper areas of the barriers $0.8 \mu m$ wide are the first to be exposed, as well as the barrier pads (first exposure). Next, a sequential manifestation of the upper three layers of the resist in the developers was carried out

After that, a second exposure was carried out to form lithography under the gate subfect with the required nominal size and dose supplement on the sites. Next, the lower two layers of the resist appeared (figure 5c, 5d).

As a result, a mushroom-shaped profile of the developed areas in the resist was formed. After that, stripping in oxygen plasma from the residues of the resist at the bottom of the developed areas is carried out.

After stripping, the necessary gate metallization is applied in oxygen plasma (figure 5e). Gate metallization based on the Ni/Au system was formed on the electron beam spraying unit. The "explosion" of metallization was carried out with dimethylformamide (figure 5f).



Figure 5. Stages of forming a mask of electronic resists to form a T-shaped gate.

The gate length, L_g , obtained by electronic lithography was 0.5 μ m. The gate metallization contacts are a set of single gates with a width of 100 μ m and are shown in figure 6.



Figure 6. Optical microscopy images of gates.

2.4. Surface passivation, formation of contact pads and inter-electric connections

Surface passivation protects the structures from environmental influences and reduces surface effects. As passivation, a silicon nitride film was used, obtained by plasma-chemical deposition using a gas mixture based on monosilane, argon, and nitrogen.

The contact pads of the drain, source, and gate are formed using explosive photolithography and electron beam sputtering of the Ti/Au system.

The source contacts are connected using air bridge technology. Herewith, it first performs photolithography of the bridge resist, which determines the height of the bridge, and then the pattern in the photoresist is exposed to temperature to form a sloping edge necessary for continuous deposition of the metal layer. Then, a Ti/Au inoculating layer is formed at the electron beam spraying unit. At the next stage, photolithography is carried out to build up galvanic gold. After growing gold, unnecessary areas of the inoculating layer are removed by chemical etching. The final operation is the removal of the under-bridge photoresist.

The image of the finished transistor structures is shown in figure 7.



Figure 7. Optical microscopy images of finished transistor structures.

After the formation of transistor structures on the plate, the operation of thinning the sapphire substrate to a thickness of 80 μ m was carried out with further laser separation into crystals. Figure 8 shows the image of the transistor crystal obtained by the technology described above.



Figure 8. Optical microscopy images of crystal transistor with periphery 8×100 um.

3. Results of measurements

On the obtained transistor crystals, an analysis of the output current-voltage and transition characteristics is carried out. Figure 9 shows the output current-voltage characteristics of transistor crystals.

700 175 700 Wg=8x100un Vg=0 V Drain current, mA/mm 600 150 ansconductance, mS/mm 튭 **600** Vg=-1 V 1/Y 500 500 Vg=-2 V 400 400 current, V=-3 V 300 300 Vg=-4 V Drain (20 200 Vg=-5 V 100 100 Vg=-6 V 0 0 0 Vg=-7 V -7 -6 -5 -4 -3 -2 -1 0 0 1 2 3 4 5 9 10 6 7 8 Gate bias, V Drain bias, V b) a)

The maximum drain current is 0.60 A/cm^2 , the steepness is 155 mS/mm.

Figure 9. The (a) output characteristics and (b) transfer characteristics of an AlN/GaN HEMT with a 0.5 um gate length.

Another important parameter of transistors is the value of the gate-drain capacitance. The value of capacitance has a key effect on the frequency characteristics of transistors. The dependences of the gate-drain capacitance on the gate voltage for the structures under consideration are shown in figure 10. At a gate voltage of 0 V, the capacitance values are 1.12 pF.



Figure 10. Gate-drain capacitance voltage on the gate.

For SHF measurements, transistor crystals were mounted on Al_2O_3 boards, as shown in figure 11. The board was formed according to standard technology using current-carrying tracks based on V-Cu-V metallization and a through-hole system.



Figure 11. Optical microscopy images of crystal transistor with periphery 8×100 um.

The SHF properties were studied on a 5230A vector analyzer. The measurement results are presented in figure 12.



Figure 12. SHF performance of the 0.5-um-gate-length HEMT.

The output power at a frequency of 3.5 GHz was 0.25 W/mm.

4. Conclusion

As a result of the research, the technology of post-growth processing of transistor structures based on gallium nitride was obtained. The key operations of manufacturing gallium nitride-based micro devices are considered, namely: the formation of inter-instrument insulation, the formation of non-straightening (ohmic) and straightening (Schottky barrier) contacts, surface passivation, the formation of inter-electrical connections in the form of "air bridges", grinding of a plate, cutting of a plate into crystals and sorting out. Experimental samples of transistor crystals with fairly high characteristics were obtained.

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