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Study of nitrogen ion implantation through Si3N4 layer for GaN on Si power HEMTs isolation process

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This letter reports a nitrogen ion implantation through silicon nitride passivation layer deposited on AlGaN/GaN on Si heterojunction structure. Employment of Si3N4 layer simplify HEMT fabrication process and helps to obtain high resistivity isolation due to the shift of implanted ions distribution towards the surface of semiconductor. This isolation process in combination with C-doped heterostructure buffer layer results in increased up to 650 V breakdown voltage.

Keywords: ion implantation, breakdown voltage, GaN, power transistor.

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High-electron mobility transistors based on AlGaN/GaN heterostructures are being actively studied for developing a next-generation semiconductor element base for Microwave-electronics and high-speed power electronics. Particularly promising here is the gallium nitride heterostructure grown on a silicon substrate due to the lower cost and larger wafer size. Parameters of GaN transistors on Si have been improved significantly in recent years due to the introduction of doped buffer layers [1], gates of *p*-conductivity [2], field electrodes [3]. Another stage of the transistor manufacturing process, work on which is permanently in progress in order to reduce leaks and increase breakdown and operating voltages, is the formation of inter-device isolation. Transistors' active regions are usually insulated using Cl_2 based plasma etching. As shown in [4], etching can cause a contact between the gate metal and the layer of two-dimensional electron gas in the mesa side wall, which causes a significant gate leak current. This problem can be avoided by insulation by means of ion implantation instead of etching. Moreover, the method of ion implantation-based isolation assures the structure planarity. A certain concentration of implanted ions leads to the formation of stable deep traps for electrons and holes that convert the semiconductor into a material having a high resistivity. Various ion types (H, He, N, Fe, C, Al, O and F) [5,6] were used for isolation by ion implantation. We have chosen nitrogen, since this gas is safe and more appropriate for producing an ion flow.

This paper is aimed at studying the process of nitrogen ion implantation through a layer of passivating silicon nitride to form inter-device isolation. This simplifies the formation of gate metallization, since the same dielectric is used for manufacturing a T-shaped gate. Moreover, ion implantation is simplified, since doping with several doses and energies can be substituted by one doping due to a shift of the implanted ion distribution maximum towards the semiconductor surface.

Ion distribution in structures was modelled using the known TRIM (SRIM) algorithm. It was necessary to assess the dose of radiation with nitrogen that suppresses the conductivity in the layer of two-dimensional electron gas, forming on the boundary of AlGaN/GaN and having an electron concentration above $10^{20}\,\mathrm{cm}^{-3}$ (direct conversion from the surface concentration known from experimental data).

It follows from the calculations that the use of silicon nitride changes the ion distribution, particularly at energies of 50 to 100 keV. When energy of implanted ions decreases, the maximum of ion distribution shifts towards the semiconductor surface into the region of the AlGaN/GaN heterointerface, so electron gas conductivity can be suppressed more efficiently. In the standard technology where implantation is performed without a silicon nitride layer, the maximum of radiation defect distribution is located much deeper than the AlGaN/GaN heteroboundary, which hinders the suppression of conductivity.

Moreover, the calculations showed a strong dependence of ion distribution on density of plasma-chemical silicon nitride. It is know that, depending on deposition conditions, the density of plasma-chemical silicon nitride varies from 2.0 to $2.8\,\mathrm{g/cm^3}$ [7]. For the Si_3N_4 we used, special measurements were made using the HR100AZ microgravity meter. The density value of $2.7\,\mathrm{g/cm^3}$ was obtained.

For the given dielectric density value, ion distributions have been calculated for the energies of 50, 70, 75, 80, 85, 90 and 100 keV. In addition, ion distribution calculations were performed for the silicon nitride density values of 2.15 and $3.17\,\mathrm{g/cm^3}$, corresponding to the amorphous and crystalline state [8]. Distribution of defects in the structure was also simulated with presence and absence of a silicon nitride layer.

The calculations showed that the maximum of defect distribution upon a change in the energy of implanted nitrogen ions can shift in depth from 60 to 300 nm, so defect concentration at the AlGaN/GaN boundary varies by more than an order of magnitude, the dose of implanted ions being equal. For the silicon nitride density of 2.7 g/cm^3 and thickness of 100 nm, the maximum of the distribution of implanted nitrogen ions is located at the AlGaN/GaN boundary, ion energies being 75-85 keV (Fig. 1). Thereat, the defect concentration at the specified boundary was more than 10^{20} cm^{-3}, implantation dose being more than 200-500 μC/cm^2. Thus, it was possible to neutralize the electron quantity, existing at the boundary of AlGaN/GaN, that had a comparable concentration.

Experiments to obtain inter-device isolation were carried out on the IBS IMC200 ion doping plant. Samples of AlGaN/AlN/GaN heterostructures on silicon with a doped and undoped transition layer (buffer) from the substrate were taken [9]. AlGaN layer thickness was 25 nm, Al concentration was 25%. Inter-device isolation was tested

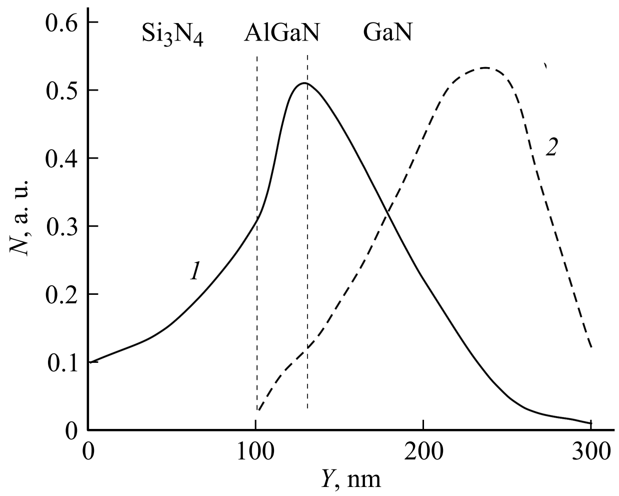

Figure 1. Distribution profiles for nitrogen ions implanted at the energy of 85 keV in the AlGaN/GaN heterostructure with a silicon nitride of 100 nm on the surface (*1*) and without it (*2*).

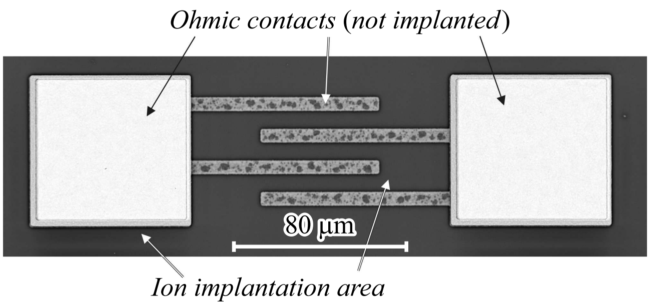

Figure 2. Image of the test structure on inter-device isolation obtained by scanning electron microscopy. The distance between the ohmic contacts was $\sim 5\,\mu$m.

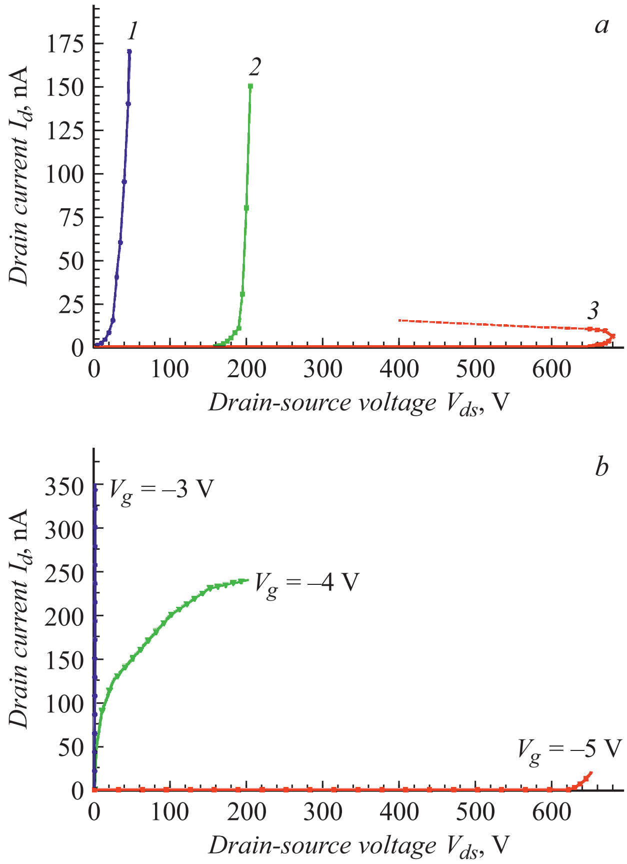

Figure 3. *a* — dependencies of leak current in the test structure on voltage between ohmic contacts. *1* — after etching in plasma BCl_3, *2* — after ion implantation with an undoped heterostructure buffer, *3* — after ion implantation with a doped heterostructure buffer. *b* — current-voltage characteristic of the test field resistor in the cut-off mode.

using a test structure (Fig. 2) made of ohmic contacts of the source and drain spaced at 5 μm and contacts pads for the measuring probe.

The pattern of the test structure was formed using bilayer protolithography, then multilayer metallization of the Ti/Al/Ni/Au-based ohmic contacts was evaporated, and the topology of the test structure was obtained by lift-off in organic solvents. Then the ohmic contacts were annealed at the temperature of 870°C and PECVD silicon nitride was deposited [10]. A sufficiently thick photoresist (3 μm) was used as a mask for ion implantation. The implantation insulated the area between the test ohmic contacts. Transistor structures with the gate length of 0.7 μm and width of 100 μm were formed along with the tests. The transistors were monitored for specific current and transistor breakdown voltage in the cut-off mode (transistor drain voltage at the transistor gate voltage when the drain current is minimum).

Nitrogen ion implantation was performed with dose increase from 100 to 1000 μC on two samples (with an undoped and doped buffer) and measurements after each

100 μC. Leak currents on the test structure were observed up to the level of 500 μC, and starting from 600 μC, the currents decreased to less than 1 nA. Breakdown voltage through the structure stabilized too. For comparison purposes, the test structure was also made by etching in low-energy plasma BCl_3 to the depth of 100 and 200 nm. Immediately upon etching, measurements showed no field leaks, but leaks increased abruptly after deposition of PECVD silicon nitride.

Fig. 3, *a* shows the measured leak currents in the test structure: leak currents after heterostructure etching and silicon nitride application (curve *1*), leak currents for undoped buffer (curve *2*), leak currents for carbon-doped buffer (curve *3*). When using a doped buffer and inter-device isolation with implanted nitrogen, there are almost no current leaks and breakdown voltage increases almost to the level of breakdown of the air gap between the contacts.

The measurements of the test transistors have showed that implantation by nitrogen ions combined with a carbon-doped heterostructure buffer allows for the making of field-effect transistors having a breakdown voltage in the cut-off mode up to 600 V (Fig. 3, *b*) and specific leak currents less than 1 nA per millimeter of gate width.

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Conflict of interest

The authors declare that they have no conflict of interest.

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