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Focused Ion Beam Methods for Research and Control of HEMT Fabrication

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Abstract. The combination of ion-beam spraying and raster electronic microscopy allows to receive images of sections of defects of the growth nature origin in epitaxial films on GaN basis with nanodimensional permission, to carry out their analysis and classification irrespective of conditions of receiving. Results of application of the specified methods for the analysis of technological operations when forming the microwave transistors are considered: formations of locks, receiving of holes and drawing of contacts.

1. Introduction
Electronic and microscopic methods are the powerful instrument of selective control of parameters of heteroepitaxial structures and substrates, and are especially urgent for improvement and optimization of the modes of engineering procedures of devices production. An urgent task is the development of techniques of incoming and technological control of heterostructures AlGaN/GaN/SiC [1]. Defects of substrates, interstices, influence of impurity at formation operations and other harmful factors introduced by technological operations interfere with receiving of the quality characteristics HEMT. Elimination of the specified shortcomings causes need of creation of techniques of the researches allowing to observe cross sections and to determine conditions of working structures in the chosen place. Combination of raster electronic microscopy of high resolution and preparation of objects of focused ion beam allows to carry out the preparation considering features of the researched object.

2. Aims and Definition of Task
The developed techniques and the equipment are intended for works on the control of quality of the substrates of silicon carbide which are used for production of heterostructures AlGaN/GaN/SiC, and also the heterostructures which are applied to creation of the microwave GaN HEMT devices. In this work the description of solutions of the following tasks is stated: 1) selective input control of the substrates intended for devices production of heterostructures on the GaN basis; 2) development of techniques of technological postoperative control of plates with heterostructures for optimization of technological procedures of an electronic lithograph, etching and metallization.
3. Technique of Researches
In this research with the equipment Helios NanoLab the following technological operations are developed and applied: the local ion-beam etching based on superprecision ionic dispersion under the influence of an focused ion beam at the high accelerating voltage; the ion-stimulated sedimentation based on local ionic activation of process at introduction to a zone of processing of chemically active gas, a source of the besieged material. The resolution of technological operations and the resolution in the microscopic mode of observation in secondary electrons realized by means of an ionic bunch of preparation made 7 nanometers and 0,4 nanometers respectively. At the same time the focused ion beam was applied to creation of cross sections of a sample perpendicular or at an angle to his surface. The analysis of cross section of a sample has allowed to distinguish borders between the materials received at different technological stages, local heterogeneity and foreign inclusions. Observation of features of structure in the depth of samples can be made not only in static, but also in the dynamic mode at ionic etching and simultaneous visual control by an electron beam.

Process of creation of cross sections included the following main stages: 1) obtaining the orthogonal image of an object (cut) for the choice of the site of preparation; 2) providing a good drain of a charge for obtaining qualitative images; 3) the rough etching deleting the main part of material before the studied object; 4) the polishing etching revealing thin structure of an object of a research; obtaining image of an object. As a result the typical cut of the studied structures represented a rectangular well up to several microns in depth, one of walls of which is polished.

Current research shows that in order to obtain high quality cross-sectional images of the grown defects in epitaxial GaN layers with the use of FIB, the removal of effects caused by the violation of the material stoichiometry is needed, because preparation and polishing by ion beam comes with implant of GaN ions related to the layer material. Resulting not-stoichiometry compound Ga1+xN was decomposing with excreting of metallic Ga in the form of drops. To remove this effect the reduction of energy and ion beam current was used with local deposition of technological platinum layer about 0.5 micron thick on the area of the defect. The platinum layer prevents ion implantation of Ga which eliminates metallic Ga drops formation. That allows increasing the contrast of image and reducing the effects of the charging of the dielectric surface. The deposition of the metal layer for the drain charge at determined surface areas was made by the source of metal-organic platinum compound.

3. The Obtained Results and Their Discussion

3.1. The analysis of initial structures GaN
Deep etching by an ion-beam method was applied to the layer-by-layer analysis of structural features of samples GaN. The modes of this process have been picked up so that they were compatible to standard operations of formation of structures of microelectronics. As a result it is received that layer-by-layer ion-beam drain allows to reveal the latent defects like emptiness and punctures which have partially geometrical facet (a hexagonal form of a pole of etching and a pyramid of growth). Existence of the latent defects like punctures is the reason of impact of implantation on depth at 5-15 times the exceeding length of a run of argon ions in gallium nitride (according to data of atomic and power microscopy and a photoluminescence) as the speed of their dispersion is 2-4 times higher than the speed of dispersion of an initial surface. The latent defects are the main channels for leakages of current after metallization. The combination of ion-beam dispersion with the FIB and SEM methods allows to receive images of sections of defects of the growth nature of an origin in epitaxial films on the GaN basis with the nanodimensional permission, to carry out their analysis and classification, irrespective of receiving conditions. Table 1 generalizes the obtained data.

During the testing of defect identification method it was revealed [2] that growth defects in layers with density higher than $10^6\text{cm}^{-2}$ are caused by the lack of epitaxial agreed substrates. They adversely affect the operating characteristics of the device structures manufactured by planar technology. Electron microscopy techniques allowed detection of large group of defects in the form of hexagonal pyramids, positioned with their base to the surface, with typical dimensions of the base up to 200 nm,
penetrating even in the substrate. GaN on Si films contain a large number of longitudinal cracks along the direction (001). Physical proximity of cracks (less than 1 µm) causes the separation of layer material from the substrate.

Table 1. Classification of growth defects in GaN based on their distribution by size and depth.

| Defect type | Defect description                                      | Defects density | Electron microscope image |
|-------------|---------------------------------------------------------|-----------------|--------------------------|
| I           | Small defects (less than 10 nm) in near-surface epitaxial p-GaN layers | $10^8 \div 10^9$ cm$^{-2}$ | ![Image](image1.png) |
| II          | Prolonged defects (up to 200 nm) through epitaxial p-GaN layer | $10^7 \div 10^8$ cm$^{-2}$ | ![Image](image2.png) |
| III         | Defects going through multilayer epitaxial GaN structure (up to 3.5 µm) | $10^6 \div 10^7$ cm$^{-2}$ | ![Image](image3.png) |

3.2. Control of T-shaped Lock Formation Processes
In recent years, speed increase of devices based on wideband gap semiconductor materials is achieved mostly with the decrease of gate length. That also allows increasing transistor transconductance and decreasing noise figure [3]. Basically microwave field transistors with Shottky barriers utilize so-called T-shaped gate. Traditionally electron-beam lithography with three-layered resist system PMMA/(PMMA&PMAA, copolymer)/PMAA is used in creation of T-shaped gates. Since that technique is based on the difference in exposure speed of copolymer and PMMA, during the formation of T-shaped gate the size of its pin will be strongly influenced by the exposure time, copolymer thickness and its chemical composition [4–8].

During testing of T-shaped gate formation process, samples of HEMT patterned gate structures with multilayered resists on different substrates (silicon, silicon carbide, sapphire), and with gate metallization, were investigated as test samples. FIB was used to obtain resist exposure profiles, to determine thickness and homogeneity of gate metallization and to reveal the resulting defects. Typical profile of T-shaped gate with three-layered resist system is shown in Figure 1.

The main results of researches of structures with the T-shaped lock have shown that defect when forming T-shaped locks is caused by the following major factors: 1) non-uniformity of resist exposure; 2) effects of contamination of edges; 3) defects of metallization.
3.3. Control over Hole Formation Processes

In transistors on the basis of heterostructures AlGaN/GaN made on silicon carbide apply through metallization that allows to take away effectively heat and reduces parasitic inductance. For this purpose apply jet and ion etching, in particular, etching in the inductive and connected plasma. The technique developed on the basis FIB have allowed to estimate depth of the etched openings, a tilt angle of walls and their morphology, and also to define the defects which are formed in the course of etching. Tests were performed on samples on semi-insulated 6H-SiC substrates 50 mm in diameter and thickness of 100 µm with back-side epitaxial GaN/AlGaN layers 2 µm thick. Typical cross section of SiC via hole with etching stopped at GaN/AlGaN layer is shown in Figure 2.

![Figure 2. Cross-section of 6H-SiC surface after the etching of non-through holes stopped at GaN/AlGaN layer.](image)

Hole depth is 100 µm, with ribbed side-walls. Ridges with different height are visible at the bottom, which are presumably pillars, appeared as a result of micromasking effects on micropipes and screw dislocations. Maximum height of the defects is 25 µm. Except that, the surface of gallium nitride could be observed, which characterizes by slow etching in fluorine based plasma. Two types of post-etching SiC surface defects were observed during the research, distinguishing by different distribution on the surface. The defects were in a form of round holes with transverse dimensions up to 50 µm. Some defects have distinct hexagonal form. Similar defects were observed in [9]. At the same time on the bottom of not through holes defects in the form of deepenings of irregular shape are observed. In the center of some defects there are small single ledges.

![Figure 1. Cross-section of T-shaped gate structure.](image)
3.4. Control of Ohmic Contacts

Creation of ohmic contacts meeting the requirements mentioned above for GaN based devices technology is still the subject of research [10]. Main requirements for ohmic contacts are smooth surface morphology, sharp (smooth) edges of contact pads, thermal stability and current-voltage characteristic linearity. Ti/Al/Ni/Au is frequently used as of ohmic contact to GaN [11]. Flaw of such system is high degree of surface roughness due to strong mixing of Au and Al. In this research, samples for the testing of methods for control of AlGaN/GaN/SiC device defects had ohmic contacts Ti/Al/Ni/Au and Mo/Al/Mo/Au. Typical thickness of contact structures are: Ti(20nm)/Al(100nm)/Ni(100nm)/Au(200nm). It is shown that areas of ohmic contacts containing Ti have protuberance-shaped defects, typical for melt of AlNiAu compounds, and the interface with titan sub-layer is not homogeneous and contains foreign inclusions in the form of separate cavities, whose size can be up to 30-50 nm. Microscope images of annealed Mo/Al/Mo/Au and Ti/Al/Ni/Au ohmic contact surface are shown in Figure 3.

![Microscope images](image_url)

**Figure3.** Microscope images of Mo/Al/Mo/Au (a) and Ti/Al/Ni/Au ohmic contact surface (b).

On typical microscopic images of cross-section of the ohmic contact Mo/Al/Mo/Au the boundary of layers GaN and AlGaN is well noticeable and layers of heterostructure and metallization are well perceptible. Metallization and AlGaN layer thicknesses are in a good agreement with data obtained during deposition and growth, respectively. Melting of metals was not observed, compared with conventional Ti/Al/Ni/Au [12].

4. Conclusion

The developed techniques of research of initial plates defects and technological control of formation of devices with heterostructures were used for tasks of optimization of technological processes of electronic lithograph, etching and metallization.

Authors consider that in this work the following provisions and results are new:

- The technique of researches of structures with GaN combining raster electronic microscopy of high resolution and nanodimensional local preparation by the focused ion beam is developed.
- Data on standard defects of growth in epitaxial layers GaN, their distribution on a surface and volume are obtained. Various defects of the substrate 6H-SiC are revealed and classified.
- The technique of quality control of drawing a rezist for formation of T-shaped locks is offered.
- Control methods of technological operations for receiving contact holes in SiC to a working layer GaN are developed and approved.

Recommendations about optimization of the modes of technological operations for creation of ohmic contacts Ti/Al/Ni/Au and Mo/Al/Mo/Au with the acceptable morphology of metallization and rather low specific resistance are formulated.

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