Effect of thermal stabilization on surface traps in the HEMT-transistors based on AlGaN / SiC

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Abstract. HEMT transistors based on the structures of the AlGaNSiC were created. All the basic characteristics of the transistors were studied and their operating parameters were determined, including power, leakage current, current saturation, etc. The influence of surface traps on the characteristics of the transistors by optical activation was investigated. The method for the passivation of traps based on thermal stabilization was developed.

1. Introduction

Currently heteroepitaxial structures of group III nitrides are actively replacing traditional Al³⁺B⁵⁻ materials on the basis of gallium arsenide in the optical [1-3] and microwave [4] electronics. Large value of the electron concentration in the channel in combination with high breakdown fields make it possible to provide a microwave power density in GaN-based field effect transistors 5-10 times larger than in GaAs-based devices. There are several problems in the operation of HEMT-nitride based transistors in microwave mode. One of the major problems is the presence in transistor structures of various defects, significantly reducing both the performance and power of the device. The critical impact on the operation of HEMT-transistors have surface traps that arise at the Si₃N₄-AlGaN interface. Actively search is being made for methods of reducing the effects of such traps on the parameters of microwave devices. The paper proposed a method of surface passivation of traps based on the use of thermal stabilization. Thus, HEMT-transistors based on AlGaN/SiC structures were created, the influence of traps on their performance was studied and ways of dealing with traps, in particular, by thermal stabilization of HEMT-transistors, were developed.

2. The samples

For the experiment, several AlGaN / SiC plates were made, on which HEMT transistors with a gate width of 300 μm and a length of 0.5 μm are placed. SiC was used as a substrate, on which the epitaxial transistor structures [5], shown in Fig. 1, were grown. The main functional layers are: barrier layer Al₀.2₃Ga₀.7₇N, sub-buff layer of AlN, GaN channel layer and the top layer Al₀.3₅Ga₀.6₅N. The plate was divided into separate transistors from which for further experiments control samples were selected to the following criteria: the saturation current was from 150 to 170 mA and a cut-off voltage was not less than 5 V, the leakage current at 60 V was no more than 300 microamps.
In the work, special attention was paid to the creation of dielectric layers in the structure and investigation of the influence of their structure on the parameters of the created HEMT-transistors. The dielectric was Si$_3$N$_4$. In the structure, two dielectric layers were created - an under the gate layer and a protective layer (Fig. 1). The layers were grown by the method of plasma-chemical deposition from the gas phase by the decomposition of silane and nitrogen. This method is relatively simple and low-cost, that determines its widespread use in the technology of micro- and nanoelectronics. At the same time, the composition and structure of the silicon nitride layers grown using this method vary greatly with the change in process parameters. A frequent problem is the deviation of the composition of such films from stoichiometry. In addition, in such dielectric layers in most cases, a significant amount of hydrogen and oxygen atoms remains. This leads to the appearance in the structure of traps for charge carriers and a significant decrease in the transistor speed. In this paper, the properties of such traps were considered and a method for effectively reducing their influence on device parameters was proposed.

3. Experiment

Created HEMT-transistors underwent comprehensive testing, including a study of the basic characteristics and determination of operating parameters. In particular, their power parameters, delay times, saturation currents, etc. were determined. Special attention was paid to detecting and investigating the properties of traps in nanostructures, as well as determining their influence on the performance characteristics of devices. The detection and diagnostic technique was based on the activation of traps by exposing them to radiation with a photon energy of 1 to 4.4 eV. During the diagnostic process, the HEMT-transistors operated in a pulsed mode at a frequency of 3.3 GHz. The characteristic photon energies corresponding to the appearance of the trap activation effect for structures of various types were determined, and the relative power increase (up to three times) and the relaxation times of surface traps, in some cases exceeding 20 s, were calculated. As a method of passivation of traps, thermal stabilization was used at a temperature of 300 degrees Celsius.

In addition to the traps, thermal effects on HEMT transistors can also have an effect on the dielectric, in this case Si$_3$N$_4$. Properties of the created dielectric layers of silicon nitride before and after the procedure of thermal stabilization were studied by optical spectroscopy, transmission, refractometric and other methods of analysis. A modification of the IR absorption spectra [6] is observed with a change in the temperature of the processes and the duration of the thermal impacts. The change in the refractive index from 1.875 to 1.84 and a small decrease in the thickness of the dielectric, on the order of 1.5 nm, was also established. The analysis of the obtained array of experimental data made it possible to single out the main changes in the structure of the Si$_3$N$_4$ layers, which occur when they are modified by the thermal stabilization. The changes in the ratio of the chemical bonds during stabilization (Figure 2) are investigated. An increase in the process temperature leads to the removal of a significant amount of hydrogen from the N-H bonds in the dielectric layer.
The impact of thermal stabilization on surface traps were investigated in detail. For this purpose, the microwave power of the transistors was measured when they were irradiated with photons with different energies. The photon flux for all energies was kept constant at 0.2 mW.

On the basis of the obtained data, special UV LEDs [7] and a measuring bench attachment on their basis were created [8-10], which makes it possible to measure the effect of external radiation on the power characteristics of a HEMT transistor. Spectral characteristics of UV LED are shown in Fig. 3.

Transistors were exposed before and after thermal stabilization. Before thermal stabilization, the microwave power of the transistors was about 400 mW. After stabilization, the power of the transistors increased significantly and could reach 1200 mW. Figure 4 shows the dependence of the additional power on the energy of the incident photons. It can be seen that when irradiated, the power of the nonstabilized transistor increases 2.5 – 3 times, while in the case of stabilized transistors the power does not change much.

It is important that this effect is observed in a wide range of the energies of the incident photons (Figure 4), including for energies smaller than the band gap of GaN, the most narrow-gap semiconductor layer. This confirms the assumption that the reduction in microwave power in nonstabilized transistors is primarily due not to the properties of semiconductor layers, but to the effect of surface traps.

Another important fact is that when illuminated, the power in nonstabilized transistors increased exactly to the values reached in the microwave mode for stabilized structures. This suggests that the effect of the traps in the structure was almost completely eliminated as a result of stabilization.
Figure 4. The dependence of the additional power of the irradiated HEMT transistor before and after thermal stabilization on the energy of the incident photons

Thus, a method of thermal stabilization was developed, which by eliminating the effect of surface traps [11] has made it possible to significantly improve the most important parameters of the HEMT-transistor, including their microwave power and speed. The method is based on a single or multi-stage impact on structures of elevated temperatures (from 200 to 350 °C). The total duration of impact ranged from a few minutes to 5 hours. Detailed studies of the effect of changes in the time and temperature parameters of stabilization on the characteristics of HEMT transistors have been carried out, and optimal treatment modes for structures have been determined, which make it possible to achieve the greatest improvement in their operating parameters.

One of the most important results achieved is the stabilization of the operating parameters of structures located in different parts of the plate. It can be seen that after thermal stabilization, the spread of the characteristics of different transistors was minimized. (Figure 5). This effect was observed not only for microwave power, but also for saturation currents and other electrical characteristics of transistors.

Figure 5. Transistors power before and after thermal stabilization

4. Conclusion

Thus, during the work, HEMT-transistors based on AlGaN/SiC structures were created. The gate width was 300 μm, the length was 0.5 μm. All the main characteristics of transistors were investigated and their operating parameters were determined, including power, cut-off voltage, leakage current,
saturation currents, etc. The effect of surface traps on the characteristics of transistors by the optical activation method was investigated, a laboratory attachment for its implementation was created and their characteristic parameters were determined. The technique of passivation of traps based on the use of thermal stabilization has been developed. As a result, a significant improvement in the parameters of the structures was achieved, in particular, the power of transistors increased on average from 26 to 32 dBm, stabilization of the saturation currents was achieved. The stabilization of the operating parameters of structures located in different parts of the plate was achieved.

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