Monolithic transistor switch for microwave radiometry

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Abstract. Modern medical microwave diagnostic equipment requires the application of solutions related to the compactness of the developed devices and high performance. Ensuring these requirements is possible by using a modern semiconductor component base based on A\textsuperscript{3}B\textsuperscript{5} compounds. One of the promising materials for this purpose is gallium nitride. The paper presents the design and manufacturing technology of one of the main control elements of the microwave signal in microwave radiothermometer - monolithic AlGaN/GaN/\textup{SiC} HEMT SPDT transistor switch.

1. Introduction

Recently, the method of microwave radiometry, which has a number of advantages over traditional diagnostic methods, has been rapidly developing for the use in various fields of human activity. Today, a promising method for measuring soil moisture, based on the use of microwave radiometric sensors of various wavelength ranges, is in the process of implementation into commercial operation. In addition, microwave radiothermometry is actively developing for the functional study of human tissues and organs, which allows non-invasive detecting thermal heterogeneities in them, performing early diagnosis of cancer and correcting the treatment process by changing the parameters of electromagnetic radiation of tissues and organs [1-2].

However, the further development of the radiometry method is hampered by a number of scientific and technological limitations that need to be overcome. Combining the principles of multi-channel, multi-frequency and microminiature in one radiometric complex will lead to a significant reduction in the size of the radiometric receiver and to the need to develop fundamentally new design and technological solutions, namely, its implementation in the form of a single module, which implies the use of a monolithic integrated design. The results of work in this direction are shown in [3-5].

Thus, modern microwave equipment requires technical solutions that ensure the compactness of the developed devices and high performance. The use of the element base, made in the form of monolithic integrated circuits, will increase the variability of circuit solutions in the development of modern microwave radiometers and, thereby, ensure their optimal characteristics and expand the functionality of the devices. In [6-8] the possibilities of using integrated circuits in medical microwave radiothermometers are considered in order to improve the characteristics and functionality of the devices.
The aim of the work is to develop a monolithic switch for designing a miniature microwave radiometer that provides stable operation of the device with an acceptable measurement error.

2. Results
Recently, there has been considerable interest in the implementation of a microwave semiconductor component base based on wide-band materials of the A3B5 group. The use of HEMT AlGaN/GaN heterostructures on semi-insulating SiC substrates in comparison with GaAs-based heterostructures, which are traditional for the microwave application, makes it possible to ensure minimal crystal sizes, efficient heat removal, and work with high input signal power values. In this regard, the use of such a component base in various microwave devices is quite promising.

The design of the monolithic switch was determined by the scope of the developed radiometer. The main requirements for switches are miniaturization and the provision of low insertion loss values and high decoupling values over a wide frequency range. The radiometers most sensitive to the response of the microwave signal from the biological object of research operate in the frequency range of 0.5-3 GHz [9]. Another essential requirement for the developed element base is to provide the radiometer with the ability to receive a signal and calibrate for the "hot" and "cold" temperature load. Based on these requirements, the design of the SPDT type transistor switch (one input-two outputs of the microwave signal) with a minimum topological size of 0.4 microns was selected to ensure reliable operation in the specified frequency range.

A domestic epitaxial HEMT structure grown by gas-phase epitaxy on a semi-insulating silicon carbide substrate with a diameter of 76.2 mm produced by Closed Joint Stock Company “Svetlana-Electronpribor” was used when developing the manufacturing technology of the transistor switch.

In the framework of this work, numerical modeling and experimental optimization of the design of heterostructures of field-effect microwave transistors (HEMTs) based on AlGaN/GaN material systems were carried out. The need to predict the most important output characteristics of transistors required the construction of models for the statistics of carrier distribution in all areas of the heterostructure, a model of differential mobility in the two main materials (GaN, AlGaN) of the heterostructure with possible doping of each, as well as careful tuning of the model of the total energy balance of carrier transport in the HEMT transistor channel to account for the heating of the main carriers and an adequate description of the current transmission processes at the submicron gate length required for the operation of the transistor as part of the switch. Widely known software packages for numerical simulation of semiconductor devices with connected modules, which implement calibrations and original numerical algorithms for calculating heterostructures, were used as basic tools for modeling and optimizing HEMT transistors [10-12]. The simulation results were compared with the experimental results of measuring the electrophysical parameters of heterostructures and HEMT transistors.

The developed heterostructures of HEMTs (figure 1) consisted of an AlGaN germ layer for SiC substrates, an insulating buffer layer GaN with a thickness of 2 microns, an AlN layer with a thickness of 1 nm, and an unalloyed barrier layer AlGaN. The thickness and composition of the AlGaN layer varied in different calculation variants in the range of 15-35 nm and 20-35%, respectively.

![Figure 1. Schematic representation of the developed HEMT heterostructure for use as a switch.](image-url)
Achieving the required basic parameters of the heterostructure - a high concentration of two-dimensional electron gas and electron mobility in the channel - is the basis for obtaining the necessary characteristics of the transistors in the switch and, accordingly, the switch itself. However, many obstacles must be overcome to achieve the desired characteristics of transistors. Let us briefly consider one that relates directly to the heterostructure. For example, it is well known that an increase in the molar fraction of aluminum in the barrier layer should radically increase the electron concentration in a two-dimensional electron gas [13]. However, such an obvious way to increase the saturation current of the transistor channel has its limitations, which is well shown by numerical modeling. The calculations performed using the Monte Carlo method, which take into account the essentially nonlinear field-velocity characteristic of the barrier layer material and include a modified mobility model [13, 14], suggest the existence of an optimal aluminum content for the selected barrier layer thickness, exceeding which significantly worsens the characteristics of the transistor due to a decrease in the electron mobility in the channel.

Figure 2 shows the values of the electron concentration in a two-dimensional electron gas and the local electron mobility under the gate, obtained by numerical calculation, taking into account the above-mentioned effects, for the barrier layer thickness of 20 nm. The obtained values are in good agreement with the experiment and serve as the basis for creating an effective transistor design for operation as part of the AlGaN/GaN SPDT switch.

As a result of numerical optimization, the HEMT structure provided the following characteristics: the concentration of two-dimensional electron gas in the channel $9 \times 10^{12}$ cm$^{-2}$ and the mobility of 1750 cm$^2$/V×sec.

The formation of metallization of ohmic contacts and wiring was carried out using the method of "explosive" photolithography. The Ti/Al/Ni/Au system was used as the metallization of ohmic contacts, followed by rapid thermal annealing at a temperature of 800 °C in a nitrogen medium. Interstitial isolation was performed by ion implantation. The formation of Ni/Au gate metallization (gate length is 0.4 microns and width is 2 mm) was carried out using electronic lithography. To avoid static breakdown and increase reliability, a triple gate was provided in the switch design. The dielectric protection was provided by applying a layer of silicon nitride. Through-ground holes were formed by plasma-chemical etching of the silicon carbide substrate followed by the process of magnetron sputtering of Ti/Au metallization. Figure 3 shows the HEMT AlGaN/GaN SPDT switch crystal on the plate.
Figure 3. A fragment of the HEMT AlGaN/GaN SPDT crystals of the switch on the plate (a) and its gate part (b).

The CVC of the switch was monitored by using the Cascade MicroTech PA-200 probe station. Figure 4 shows the typical CVC of a HEMT AlGaN/GaN SPDT switch crystal.

![Figure 4](image)

Figure 4. The CVC of the switch HEMT AlGaN/GaN SPDT crystal.

The microwave characteristics were measured by using a test bench consisting of the Cascade PM5 probe station and the Rohde&Schwarz ZVB-20 vector analyzer directly on the chip without using a microwave test board. Figure 5 shows the key characteristics of the developed switch—the loss of passage and the isolation of the closed channel.
Figure 5. Low-signal microwave characteristics of the HEMT AlGaN / GaN SPDT switch.

According to the presented data, the developed switch provides losses in one channel for the passage of a microwave signal of 0.66-1.27 dB and isolation of no worse than 25-11.5 dB in the frequency range of 0.5-3 GHz. When matching the developed switch on the test board (figure 6), there is an improvement in the key parameter - the loss of the microwave signal per pass of 0.39-0.9 dB, the VSWR value does not exceed 1.33 dB, and the isolation changes in the specified frequency range from 26 dB at 0.5 GHz to 14 dB at 3 GHz, that should be taken into account when matching the switch crystal when mounting in the housing of the microwave radiometer.

Figure 6. HEMT AlGaN / GaN SPDT switch on test board.
3. Conclusion
Thus, the design and manufacturing technology of the HEMT AlGaN/GaN SPDT switch on a domestic heterostructure on a semi-insulating silicon carbide substrate are presented. The measurements of the microwave parameters of the developed switch show the possibility of using this element component base as part of microwave radiometers, which will allow combining the principles of multi-channel, multi-frequency and miniaturization in one radiometric complex and will lead to the expansion of its functionality and a significant reduction in size.

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