The Instability of the CV Characteristics’ Capacitance When Measuring AlGaN/GaN-Heterostructures and the HEMT-Transistors Based on Them

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Abstract—AlGaN/GaN heterostructures and AlGaN/GaN/SiC HEMT-transistors’ Schottky barriers (SBs) are studied by the capacitance—voltage (CV) method and the SIMS method in order to determine the causes of the capacitance instability in some cases. It is shown that in most cases, the appearance of a capacitance peak on the CV curves at frequencies of 20 to 500 kHz is associated with the presence of leakage currents in the barrier layer and at low frequencies of 1 to 20 kHz with the generation—recombination centers.

Keywords: AlGaN/GaN heterostructures, Schottky barriers, HEMT-transistors, CV method, sequential and parallel substitution schemes, hodograph of the circuit’s impedance, generation—recombination centers

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INTRODUCTION

The stationary capacitance spectroscopy of semiconductor heterostructures has shown itself to be a sufficiently effective method for studying the electronic properties of the heterostructures and the instruments based on them, because this method provides information on the amount of charge and its distribution in the active structural elements. In particular, in the case of nitride heterostructures of the AlGaN/GaN type, the capacitance—voltage (CV) method is employed to determine the position of the channel of two-dimensional electron gas (2DEG channel) and the position of the energy levels in the quantum well (QW), as well as to retrieve information on the distribution profile of free carriers in the heterostructures and active regions of transistors based on them, using the numerical processing of the CV curves [1–4]. However, it was mentioned in some works [5, 6] that the observed capacitance instability of a series of heterostructures while plotting the charge depth profiles and determining the depth of the 2DEG-channel makes the results obtained by the numerical processing of the CV ambiguous, due to the difficulty in correctly interpreting the experimental data. Such an instability was mentioned in [5] in the form of the increased capacitance during the measurement of AlGaN/GaN structures with the barrier layer intentionally doped with silicon. An analogous instability with an increase in capacitance was observed in [6] in the form of an intrinsic peak on the CV during the transition from enhancement to depletion, both in the case of the initial heterostructures with a thick (5–7 nm) upper undoped i-GaN layer (the “cap” of GaN) and the reference Schottky barriers (SBs) based on them. In the case of epitaxial AlGaN/GaN heterostructures grown on carbide, sapphire, or silicon, the correct interpretation of the observed CV is complicated by several reasons, such as the less than ideal transitions between layers and the presence of uncontrollable impurities at the interfaces, as well as the intermediate defect layers. Therefore, the calculation profiles, which are obtained during the formal numerical treatment of the CV, are usually designated as the effective or apparent carrier depth profiles [3]. In this case, a sequential substitution scheme is used. Moreover, the complication of the design of nitride heterostructures, namely, the introduction of special near-surface and spacer layers of various thicknesses with the aim to increase the operational stability of instruments and their radiation stability, variation of the molar content of aluminum in the barrier layer, as well as the layer thickness and the features of the arrangement of layers relative to each other to search an optimal technological variant [7], requires additional studies of the parameters of heterostructures. Therefore, further studies of the CV of nitride heterostructures in the broad frequency range is of some interest in order to determine the possible reasons for the appearance of various deviations of the characteristics and investigate the effect of these deviations on the instruments’ parameters.

The aim of this work is to carry out an integrated study of frequency dependences of the CV of both the initial AlGaN/GaN heterostructures and the gate—
source and gate–drain SB regions of the crystals of HEMT-transistors formed on nitride heterostructures to investigate the reasons for the appearance of capacitance instability in some cases.

THEORETICAL BACKGROUND

In [8], a sufficiently simple model is given, using which we can rationalize some electrical characteristics of AlGaN/GaN HEMT-structures, in particular, the current–voltage. The electrical scheme is separated into the external and internal parts. The external part involves the elements of a transistor (the parasitic resistances of the drain and source regions), while the internal part is represented by the elements of the heterostructure (the capacitance and resistance of the barrier and channel layers and parasite capacitance and the resistance of the buffer layer) (Fig. 1).

During a direct measurement on heterostructures, only the internal scheme is analyzed. In this case, during the measurement of the СV characteristics at various frequencies according to the sequential scheme (when there is no capacitance dispersion, when $C_{\text{max},f} = C_{\text{max},fp} = C_{\text{max}}$), the accumulation capacitance should correspond to the calculated capacitance at all frequencies. In addition, the CV characteristics have a standard form with a relatively sharp decrease in the capacitance with the transition from enhancement to depletion. In the case of the analyzed heterostructures and instruments based on them, with an increase in the bias voltage (in absolute value) to the depletion range, the voltage mainly decreases in the barrier layer. In this case, the channel is filled with electrons and represents a conducting electrode to the barrier layer. With an increase in $U_{\text{bias}}$ to the depletion range (usually in the range of $U_{\text{bias}} = -2$ to $-2.5$ V), the rearrangement of the voltage drop occurs between the barrier layer and channel due to the decrease in the concentration of the electrons in the quantum well.

Trapping centers may exist in the barrier layer [9]. If their charge does not change during the change of the bias voltage, their presence leads to the bias of the CV characteristics along the x axis without a change of capacitance $C_{\text{max}}$ in Eq. (1) (Fig. 1). If the change of the voltage in the barrier layer leads to a recharge of the traps, a change in the measured capacitance should be observed. This is possible if the current that flows through the structure changes with the change in $U_{\text{bias}}$. A fraction of the flow of free electrons may be presumably captured in the traps and return to the conductivity area creating an additional charge on the traps. It is reasonable to suggest that the additional charge on the traps may also change with a change in the current. Then, when the reference signal with a particular frequency is received, an alternating charge appears on the traps in the structure. Depending on the value of the constant current, the frequencies of the reference signal, and the ratios of the time of the electron capture by the traps to their emission period in the conductivity zone, various values of the measured differ-

$$1 = \frac{1}{C_{\text{bar}}} + \frac{\omega^2 \tau_{\text{bt}}^2}{C_i + C_{\text{bar}}} + \frac{\omega^2 \tau_{\text{buf}}^2}{C_{\text{buf}}}.$$
The instability of the CV characteristics’ capacitance should be observed. In this case, it should be noted that the traps may exist not only in the bulk barrier layer but also at the AlGaN–GaN interface. In Fig. 1, this is reflected by the introduction of resistance $R_{\text{bar}}$ (defines the constant leakage current) and the $R - C_1$ circuit (defines the recharge of the traps). The presence of traps, which affect the capacitance during measurement, may lead to its instability. To analyze the distribution of the traps, we can use the standard capacitance procedure to determine the profile of the charged centers of the free carriers by measuring according to the sequential substitution scheme [1]. In the reverse bias range, where the applied voltage drops completely in the barrier layer, and at a low concentration of the free carriers for the charged traps $N_{(x)}^-$, we can write that

$$N_{(x)}^- = 2\left(\varepsilon\varepsilon_0qA^2\frac{d\left(\frac{1}{C^2}\right)}{dU}\right)^{-1}. \quad (2)$$

When there is a weak effect of leakages in the barrier layer, Eq. (2) would describe the distribution of the charge carriers in the quantum well channel.

If there is no trap recharge while the current flows through the barrier structure, then, there are no elements $C_t$ and $R_t$ in the equivalent circuit (Fig. 1) and Eq. (1). To analyze this circuit and understand the possible reasons for the appearance of capacitance instability, it is reasonable to refer to the known relationships of the active and capacitance resistances of the high-ohmic layers in an alternating electric field. In particular, the impedance hodograph of a sequential circuit can be plotted [10, 11]; i.e., the dependence of the reactive resistance $Z'' = \frac{1}{\omega}C_{\text{max}}'(\omega)$ on active resistance $Z' = R_{\text{max}}'(\omega)$, while measuring in the broad frequency range.

In Fig. 2, an example of the (a) simplest $R - C$-circuit and (b) the hodograph plotted for it according to the sequential substitution scheme when varying the frequency in the range of $\omega = 0 - \infty$ are given. In this case, the hodographs appear as semicircumferences, which are supported on the x axis (Fig. 2b). If there are regions $Z''(Z) - Z''_{\text{arc}}(Z)$ on the hodograph which can be considered as the arcs of circumferences, then, the elements of the equivalent circuit $C_{\text{max}}$ and $R_{\text{max}}$ and the corresponding $R_{\text{bar}}$ and $C_{\text{bar}}$ do not depend on the frequency in this frequency range. A deviation from the arc shape of the circumference may indicate that the mentioned circuit parameters depend on the frequency or there are additional elements of the circuit.

**SPECIMENS AND METHODS OF STUDY**

The study objects represented both AlGaN/GaN heterostructures and the crystals of HEMT transistors formed on nitride heterostructures.

The heterostructures with the upper passivating $i$-GaN layer with a thickness of 1.0 of 2.5 nm were investigated. The AlGaN barrier layer thickness, both doped and undoped, was 20–25 nm at the molar Al content of 0.27 to 0.3. As a spacer layer, the AlN layer with a thickness of 1.0 to 2.0 nm was used, while the buffer layer was represented by the GaN layer with a thickness of 2.5 to 3 μm. In addition, the crystals of powerful AlGaN/GaN/SiC UHF-transistors of the Х-range with a gate length of 0.25 μm with various numbers of fingers and a metallized output of the source region to the inverse side of the substrate were investigated. The initial heterostructures represented the upper undoped $i$-GaN layer (with the thickness of this layer ranging from 2.0 to 5.0 nm) and spacer layers of various thicknesses. The barrier layer represented the undoped AlGaN layer with a thickness of 15 to 20 nm. The epitaxial layers of all the AlGaN/GaN heterostructures were formed using MOCVD-technology on SiC substrates with the (0001) orientation of the work-
ing surfaces. During the formation of the crystals of the devices for the formation of ohmic contacts to the drain and source regions, the Ti—Al—Mo—Au or Ti—Al—Ni—Au composition was used. As dielectric passivating layers, SiON layers with the oxygen-to-nitrogen ratio of 10 to 20% were employed.

The CV characteristics were measured on a CSM/WIN System setup in the frequency range of 1 kHz to 1 MHz in the planar arrangement of the measuring probes. When investigating the initial heterostructures, a mercury probe with a diameter of 800 μm was used. The contact area of the second probe exceeded the measurement probe area by a factor of 38. During the capacitance measurements on the crystals of the devices, the CV of the gate–drain and gate–source SB regions were recorded using gold probes. The capacitance dependences were recorded both according to the parallel (index p) and sequential (index s) substitution schemes with the additional evaluation of the change of the conductivity vs. the frequency in the sequential substitution scheme. Derived from the CV characteristics, the charge distribution profiles by depth were plotted in some cases at various frequencies using Eq. (2). In addition, in order to specify the layer depth distribution in the heterostructures and the analyzed crystals of the devices, a layer-by-layer elemental analysis of the main elements (Al, Ga, and the alloying impurity of Si) was carried out using secondary-ion mass-spectroscopy (SIMS) on a Cameca IMS 4f instrument. During the analysis of the dielectric barrier layer (without doping), a low-energy electron gun was used to neutralize the charge, while the primary ions were represented by Cs⁺. The sputtered crater depth was measured using an optical profilometer.

RESULTS AND DISCUSSION

In Figs. 3a and 4a, the depth profile of the principal elements (aluminum, gallium, and silicon) obtained using the SIMS method in the case of the two analyzed heterostructures, namely, the standard heterostructure with undoped AlGaN layer and a model with a partially silicon-doped barrier layer, is given. In Figs. 3b and 4b, the CV characteristics are given for these two structures, which were measured using the mercury probe at frequencies ranging from 10 kHz to 1 MHz. In Figs. 3c and 4c, the depth profile of the structures of the conducting channels, which was obtained in accordance with Eq. (2) from the results of the CV measurements, is given. In the case of the standard structure with an undoped barrier layer, there is a close agreement of the arrangement of the two-dimensional gas channel, which was obtained after treating the CV characteristics and according to the SIMS data (Figs. 3a, 3c), and there is also a close agreement of the thickness of the active layers of a heterostructure (SIMS) with the thicknesses of these layers indicated in the certificate. Analysis of the results of the capacitance measurements showed that, in the case of structures with an undoped barrier layer, the CV characteristics have the standard form. The capacitance of the barrier layer in the accumulation is $C_{\text{max}} = 1900–2000$ pF and almost corresponds to $C_{\text{calc}}$, and the capacitance in deep depletion is $C_{\text{min}} = 2–3$ pF (Fig. 3b).

When heterostructures with a partially silicon-doped AlGaN barrier layer were measured (Fig. 4a), an additional peak was usually observed on the CV at the measurement frequencies of $f < 200$ kHz in the transition range from enhancement to depletion, with the growth of this peak with a further decrease in the measurement frequency (Fig. 4b).

An analogous peak was observed on the CV of the gate–drain and gate–source SB systems of the HEMT transistors, while measuring according to the sequential equivalent circuit, and in particular, in the case of the gate–drain system at frequencies of <200–3000 Hz for various devices (Figs. 5a, 5b, 6a). These devices were formed on heterostructures with a complex profile and some heterostructures possessed thick upper layers of $i$-GaN (5.0 nm). During the investigation of the crystals of transistors using SIMS in active regions (the metallization layers were first removed), a deep depletion of the near-surface region (10 nm) with aluminum was observed.

In Fig. 5, the results of the measurement according to the sequential and parallel equivalent circuits of the CV of the gate–drain SB ranges are given for the analyzed 6-finger transistors, which were formed on heterostructures with a thick upper $i$-GaN layer (5.0 nm) and a spacer AlN layer. The characteristics were recorded in the frequency range from 10 kHz to 1 MHz at the bias voltage from −3.5 to 0 V. Using the parallel equivalent circuit, the dependences of conductivity on voltage were also recorded at various frequencies (Fig. 5c), while the sequential circuit was employed to record the change of resistance $R_s$ vs. voltage $U_{\text{bias}}$. As follows from Figs. 5a and 6a, an intrinsic peak, which is analogous to the peak observed at measuring on heterostructures with a doped barrier layer (Fig. 4b), is also observed on recording the CV according to the sequential equivalent circuit at low frequencies ($f < 200$ kHz) at $U_{\text{bias}}$ ranging from −2.0 to −2.8 V. In this case, the peak value also increased with a decrease in the measurement frequency. When using the parallel equivalent circuit, the $C_p$–$F$ curves possessed the standard form at all measurement frequencies (Fig. 5b) and intrinsic peaks were recorded only at the lowest frequencies ($f < 10$ kHz). However, in this case, the peak was recorded in the conductivity vs. the bias voltage curves in the same frequency range, whose height near some crystals of the instrument did not vary with frequency (Fig. 5c), while it drastically increased with an increase in the measurement frequency for some of them (Fig. 6b). The presence of conductivity peaks while measuring according to the parallel equivalent circuit was observed in [12]. In addition, during the
operation with transistors possessing a large gate width (40-finger transistors), an increase in capacitance was observed, along with an intrinsic peak, at low frequencies when using the sequential measurement scheme in the range of deep depletion ($U_{\text{bias}} = -7$ to $-3$ V). It should also be noted that, at frequencies $f = 6$–$30$ kHz, the capacitance value usually exceeded that in the enhancement mode $C_{\text{enh}}$ (Fig. 6a).

In Fig. 7, two types of hodographs, which were plotted according to the experimental results of the...
measurement of the $C_s-V(f)$ and $R_s-V(f)$ characteristics of the two structures in the frequency range from 3 kHz to 1 MHz at various bias voltages, are given. In Fig. 7a, the hodograph is given for one of the crystals of a transistor with a low height of the additional capacitance peak of the instability, while in Fig. 7b, it is given for a structure with a large peak height.

As follows from Fig. 7, the experimental points of the hodograph in Fig. 7a are sufficiently well described by the elements of the circumferences for the bias voltages in the range of $U_{bias} = -2$ to $-3$ V, that is, in the range of the peak of the unstable capacitance. However, in the case of the hodograph in Fig. 7b, in the crystal of the transistor with a high degree of capacitance instability, the dependences $Z''(Z')$ are sufficiently clearly described by the elements of the circumferences only at frequencies higher than 50 kHz; at lower frequencies, a significant deviation from the arc elements is observed.

In the case of the experimental model specimen with a partially doped barrier layer, an intrinsic peak (Fig. 4b) is observed on the CV with the transition from enhancement to depletion during the measurement at low frequencies ($f < 200$ kHz), whose height also grows with a decrease in frequency.

Particular difficulties were previously mentioned during the interpretation of the results of the numerical processing of the CV using Eq. (2). Nevertheless, processing the CV of the model specimen showed the presence of two peaks of the charge concentration, one of which (with an error of ±1.0 nm) coincides with the location of the boundary of silicon-doped and undoped AlGaN layers (Fig. 4a, boundary I–I). The position of the second peak coincides with the arrangement of the channel of two-dimensional electron gas according to the SIMS data (Fig. 3, boundary II–II). Thus, the combined analysis of the initial heterostructures using the SIMS method and capacitance measurements experimentally proved that the presence of the silicon-doped region in the barrier layer leads to the appearance of a second charge peak (Fig. 4c), which is presumably related to the traps, at the boundary of the doped and undoped regions of the barrier layer (Fig. 4a, boundary II–II). The presence of this peak resulted in the appearance of an intrinsic peak on the CV during the measurement at low frequencies in the transition range from enhancement to depletion (Fig. 4c). In this case, the appearance of a peak of the
It is known [13] that ionic alloying may create a forward front of intrinsic point defects in the material. The presence of these defects during the subsequent activating annealing of the heterostructures may give rise to the formation of a chain of defect formations. These defect centers in the barrier layer may represent deep trapping centers. The time constant of these centers is such that they appear at the low measurement frequencies forming the charge in the barrier layer, which provides an increment in capacity.

The observed capacitance drop with an increase in depletion is presumably related to the rearrangement of the voltage between the channel and the barrier layer. With an increase in the depletion voltage (in absolute value), there is a depletion of the channel with free carriers, an increase in the drop of the voltage in the range of the space charge of the quantum well, a decrease in the current flow through the structure, and, consequently, a decrease in the additional charge. If the traps are deep centers, their contribution to the measured capacity must lead to the frequency dependence of the measured resistance and capacity.

In contrast, the reason for the appearance of the instability peak in the capacitance while measuring according to the sequential equivalent circuit can be the leakage currents in the barrier layer, which can be related to the presence of a chain of the same defects at the doped–undoped layer interface in the barrier layer. These defects may act as current-conducting interfaces or lead to the appearance of the hopping conductivity in the AlGaN layer.

As mentioned above, the plot of the impedance hodograph of the RC-circuit provides an understanding of the relationship of the change of the active and reactive resistances of the structures while measuring according to the sequential substitution scheme at various frequencies and various bias voltages. In this case, we can evaluate the influence of the generation-recombination processes on the values of $R_{\text{bar}}$ and $C_{\text{bar}}$, that is, determine the dependences of these parameters of the equivalent circuit on frequency. As follows from Fig. 7a, the hodographs are described well for one of the structures in the range from 3 kHz to 1 MHz by the elements of the circumference for the bias voltages at which the instability peak is observed. Consequently, the leakage currents play the main role in the appearance of the peak. It is clear in Fig. 7b that, at high frequencies ranging from 30 kHz to 1 MHz, the hodographs are described sufficiently well by the elements of the circumference and the leakage currents play the predominant role. Consequently, these parameters do not depend on frequency; however, in the frequency range of $f = 3–30$ kHz, the effect of the generation-recombination processes in the barrier layer is possible.

Thus, the appearance of an instability peak at high frequencies is to a large extent related to the presence of leakage currents in the barrier layer. At lower frequencies, the defects in the barrier layer, depending on the quality of the heterostructures, may lead to leakage currents and affect the generation-recombination processes. It was shown in [14] that deep levels may
also result in the hysteresis of the CV of nitride heterostructures.

The formation of an analogous intrinsic peak on the CV curves was also recorded while measuring the $i$-GaN/AlGaN/GaN heterostructures with a thick (>5.0 nm) upper $i$-GaN layer, which is presumably related to the formation of the second counterchannel of two-dimensional electron gas at the $i$-GaN/AlGaN interface. There is a variety of localized boundary states on this interface, which can be in the $i$-GaN–AlGaN region: structural defects, impurity atoms, and grain boundaries in GaN. For example, it is well known that dislocations and grain boundaries in GaN are negatively charged [15]. The segregation of oxygen in the extended defects in GaN is also known [15]. It is mentioned in [16] that the density of these localized states in the boundary region may amount to $3 \times 10^{12}$ cm$^{-2}$, while in [17] the capture of electrons in the barrier layer from the passivating layer of a dielectric with the formation of an additional conductivity channel was considered. However, the reasons for the appearance of capacitance instability in the case of heterostructures with a thick $i$-GaN layer are still unclear and further analysis is necessary.

A drastic increase in the capacitance on the CV of the gate–drain and gate–source SB systems at lower frequencies at a significant depletion ($U_{\text{bias}} > -5$ V) (Fig. 6a) was recorded only on SBs of the crystals of the instruments and was never observed in the capacitance measurements of the initial heterostructures. In addition, the capacitance value at lower frequencies ($f < 100$ kHz) would exceed the capacitance value in enhancement (Fig. 6a). This is presumably related to the lateral expansion of the space charge field at a deep depletion from the gate towards the drain regions. In transistors, this may result in a drastic increase in the electric field at the edge of the gate towards the drain region (Fig. 6c). However, further studies are necessary for the correct rationalization of the increase in capacitance in deep depletion at low frequencies during CV measurements.

**CONCLUSIONS**

The possible reasons for the appearance of capacitance instability in the form of an intrinsic peak of the increase in capacitance on the CV of heterostructures with a silicon-doped barrier layer and structures with a thick undoped upper $i$-GaN layer, as well as in some crystals of HEMT transistors, have been analyzed.

It has been shown that leakage currents through the barrier layer are one of the possible reasons for the appearance of capacitance instability while measuring at frequencies higher than 30 kHz. Traps (generation–recombination centers) in the barrier layer and at the AlGaN–GaN interface, which contribute to capacitance measurements, can be another possible reason, particularly while measuring at frequencies of less than 20 kHz.

The possibility of the employment of an impedance hodograph of an $RC$-circuit to determine possible reasons for the appearance of capacitance instability has been experimentally demonstrated.

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