

I–V and C–V characteristics and interface electron states of Al₂O₃/AlGaN/GaN structures

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Abstract

This paper analyzes properties of the dielectric/AlGaN/GaN system with an ALD Al₂O₃ film as a dielectric. It was investigated how the current flow process in the system changes due to the deposition of films with different thicknesses; at what bias voltage the electron emission process from the boundary states begins, and how the properties of the barrier layer in the initial heterostructure affect the parameters of the current in the system. It was found that a positive charge forms at the Al₂O₃/AlGaN interface, the charge magnitude increasing with the film thickness. It was also shown that film deposition affects the charge magnitude in the channel. It was demonstrated that the frequency at which C–V measurements are carried out affects D_{it} , i.e., the distribution of the electron states at the boundaries of the Al₂O₃/AlGaN/GaN system. It was shown that the density of the detected donor-like states increases abruptly with an increase in the measurement frequency. It was furthermore demonstrated that a correctly chosen measurement scheme allows one to estimate the potential contribution of the two boundaries, i.e., AlGaN/GaN and Al₂O₃/AlGaN, in this case, some of the electrons may remain in the channel.

Keywords

heterostructures, ALD deposition, electron emission, fixed positive charge, electronic interface states, donor-like centers

1. Introduction

Despite the great interest to GaN based nitride heterostructures [1–4], there is still no clear understanding of the processes leading to the instability of the frequency and power characteristics occurring during the operation of high-power UHF devices based on the above structures. It is believed that the cause of the loss of output power due to the “gate delay” effect, i.e., the frequency-dependent phenomenon consisting in an abrupt drop or even collapse of the drain current, is the presence of

slow donor-like surface states associated with dangling bonds, and the emergence of dislocations and adsorbed ions on the heterostructure surface [2–5]. However, when it comes to specific cases, there is yet no clear understanding of the actions required to eliminate the above drawbacks. The problem of surface traps in the AlGaN/GaN-HEMT transistor technology is commonly solved by synthesizing passivating dielectric layers which partially eliminate the surface states, thus producing electron states at the dielectric/semiconductor interface [2, 4, 6]. The presence of the above states, as well as those at the dielectric/AlaN/GaN system boundaries, can sig-

nificantly affect the output of the process cycle, due to the uncontrolled charging and recharging of the electron states at the system interfaces [4–6]. At the same time, the use of a thin dielectric layer under the gate (MIS) is increasingly often used in HEMT transistors, because there are indications that isolated gate GaN HEMT have advantage over Schottky barrier transistors due to lower gate leakage currents [5]. Despite the important role of dielectrics in the HEMT transistor technology, there is no clear understanding of the origin and properties of the electron states at the boundaries, e.g. the charge density distribution depending on the energy of the centers, as well as the type of charge (donor or acceptor) for different dielectrics [7]. However, the range of dielectrics used in the nitride device technology broadens quite rapidly. Of special interest are Al_2O_3 films which currently show the best performance among the dielectrics used in the high-power MOS device technology due to their large band gap, relatively high dielectric permeability, and high breakdown voltage [3, 7, 8]. It was shown that achieving good gate control in MOS HEMT requires the use of thin (20–30 nm) Al_2O_3 layers, and such films have since recently been often synthesized using the chemical vapor deposition (CVD) method. The latter method is based on a self-limiting gaseous phase chemical process, allowing one to synthesize homogeneous and conforming thin films. An ALD growth cycle includes four stages:

- self-limiting reactions between the structure surface and the first reactant (precursor);
- blowing for the removal of unconsumed reaction products;
- self-limiting reactions between the second and the first reactants adsorbed on the surface;
- additional blowing.

Due to the complexity of the process, the typical film growth rate is 0.05–0.1 nm/s per cycle, i.e., it allows the precision control of the film deposition rate [3]. It is furthermore desirable to know the properties of the interface between the working structure and the deposited film. It has already been shown that $\text{Al}_2\text{O}_3/\text{AlGaIn}/\text{GaN}$ -MOS HEMT have higher charge concentration in the 2DEG as compared to passivated devices, e.g. Si_3N_4 . Moreover, the Al_2O_3 – AlGaIn interface has a higher quality in comparison with e.g. HfO_2 – AlGaIn with a smaller hysteresis and a lower density of states [3, 9]. Although there are a number of technological and research achievements, only little data are available on how the density and charge type of boundary states depend on the thickness of ALD Al_2O_3 films, whether there is charge redistribution in the channel upon film deposition, and how the capacity of the $\text{Al}_2\text{O}_3/\text{AlGaIn}/\text{GaN}$ structures change upon biasing. Furthermore, there is no clear understanding of the process of current flow in depleted and enriched regions of dielectric-containing structures, more specifically, how the quality of barrier and buffer layers in the initial heterostructures affects the leakage currents in such thin structures.

The aim of this work was to study the following processes occurring in the $\text{Al}_2\text{O}_3/\text{AlGaIn}/\text{GaN}$ system:

- change in the capacity and density of electron states at the $\text{Al}_2\text{O}_3/\text{AlGaIn}/\text{GaN}$ system boundaries and how charge concentration in channel change when using dielectric films of different thicknesses;
- change in the current flow process in the system upon the deposition of ALD Al_2O_3 films having different thicknesses, more specifically, at which bias electron emission from the boundary states to the conduction band starts and how the properties of the barrier layer of the initial heterostructure affect the currents in the system;
- the effect of external electric field on the current flow processes in the $\text{Al}_2\text{O}_3/\text{AlGaIn}/\text{GaN}$ system, more specifically, on the recharging of the electron states at the system boundaries.

2. Experimental

The initial heterostructures were AlGaIn/GaN Ga-polar nitride structures grown using the metal-organic chemical vapor deposition method (MOCVD) that are used for the fabrication of HEMT transistors. The heterostructures were grown on leucosapphire (Al_2O_3) and silicon carbide (SiC) substrates with 2.2–2.4 μm GaN buffer layers and 22–25 nm $\text{Al}_x\text{Ga}_{(1-x)}\text{N}$ barrier layers containing a 26–28 % molar fraction of Al.

Before Al_2O_3 film deposition, the structures were subjected to washing, degreasing, and deionized water rinsing. The Al_2O_3 layer was deposited on an Atomic Premium Plant (Korea). The Al source was trimethylammonium (TMA) precursor. The Al_2O_3 film was deposited in an oxygen (O_2) gas atmosphere acting as the process gas, or in water vapor. The carrier and blowing gas was argon. Oxygen or water vapor and TMA were interchangeably injected into the reactor chamber in pulsed mode so to provide for layerwise Al_2O_3 deposition. TMA precursor and oxygen injection was interchanged with 5 s argon blowing cycles. The deposition temperature was $T = 300^\circ\text{C}$, the background pressure being 0.36 Torr (~48 Pa). The deposited film thicknesses were 8–10, 17–20, 33–35, 50–54, and 90–100 nm. A separate experiment was also conducted for two heterostructures grown on SiC and Al_2O_3 substrates. The first deposited thin oxide film was chemically removed (HF, 30–60 min). The complete removal of the oxide film was verified using capacity and I–V measurements, and then, after washing, new, thicker films were deposited onto the structures. The thickness of the deposited films was measured on silicon satellites using an ellipsometer L116S300 STOKES ELLIPSOMETER (Gaertner Scientific Corporation, USA). The measurements showed that all the deposited films had a refraction index of 1.55 to 1.65.

The measurement of the C–V characteristics remains the most efficient method of characterizing the electrophysical properties of nitride heterostructures, due to the possibility of obtaining information on the quantity

of charge in the channel, the capacity parameters of the dielectric, the depth profile of the carrier concentration in the layers, and the presence of fixed and mobile charges in the dielectric/semiconductor system [10]. Combining the two methods, i.e., the measurement of the C–V and I–V characteristics, one can solve the abovementioned tasks, because I–V measurements are useful for understanding the mechanisms of current flow processes in the test systems, as well as the origins of leakage currents [2, 5, 12]. The measurements were carried out on a CSM/WIN System in the 10 kHz to 1 MHz frequency range with planar measuring probe arrangement and the second electrode located on the specimen surface. The following three measurement schemes were used:

1. Mercury probes, of which the second mercury probe is circular and the 800 nm diam. working capillary

probe is located in the center of the circular probe. The area of the second probe is 40 times that of the working one, both probes being located on the working surface of the specimen, i.e., in fact, this is a measurement scheme with two mercury Shottky barriers.

2. Gold probes that are installed on 700 μm diam. Ni contact pads synthesized by vacuum deposition of nickel on the working surface of the specimen. Thus, this is a measurement scheme with two nickel Shottky barriers.

3. Capillary mercury probe used an Ohmic contact, i.e., the measuring probe is a mercury Shottky barrier and the second contact is Ohmic.

For the third scheme option, it is preferable to form four Al/Ti Ohmic contacts on one of the structures using a conventional technology and then to deposit a 20 nm ALDAl₂O₃ film on the structure surface, so the distance

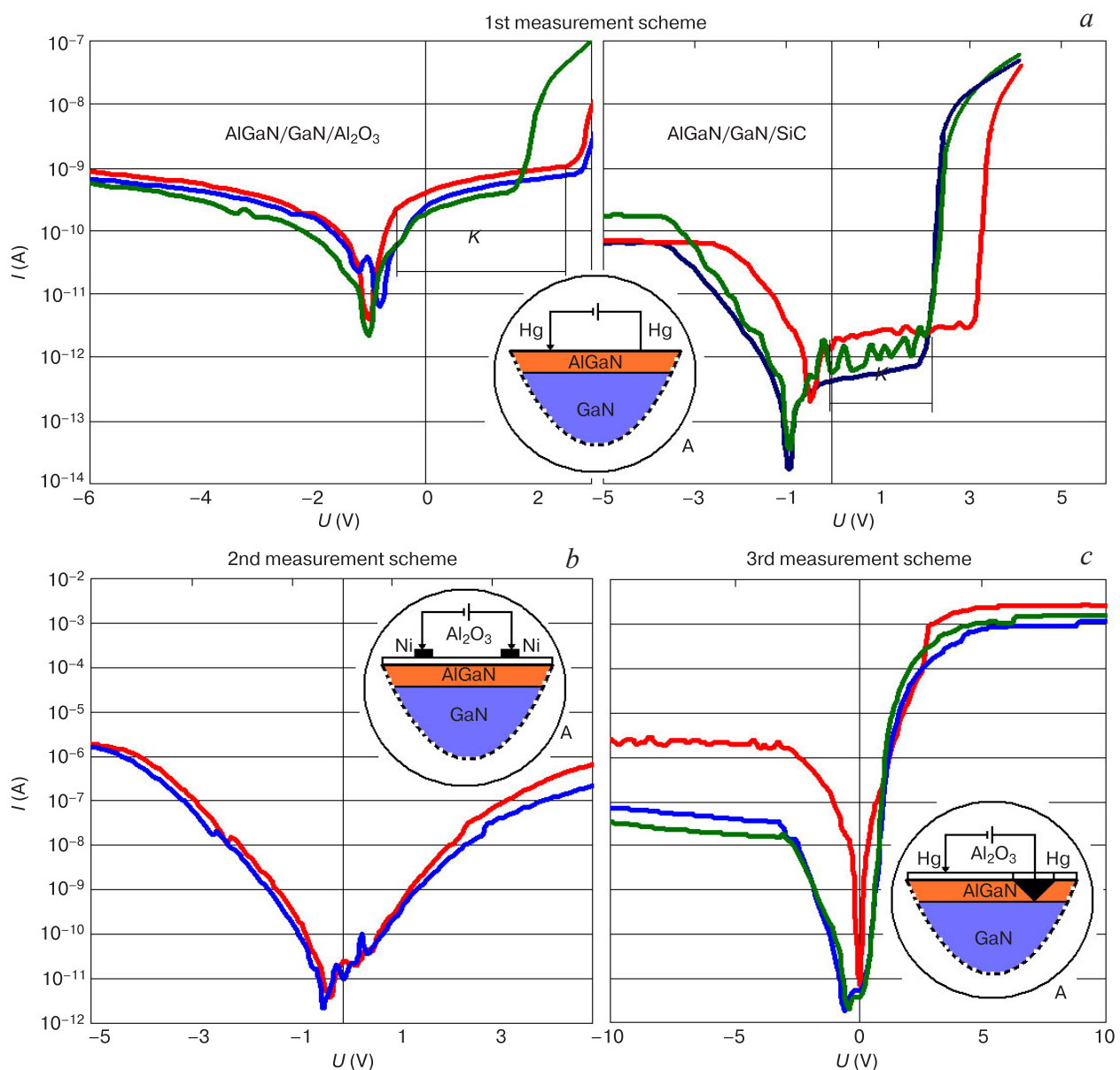


Figure 1. I–V characteristics of initial heterostructures and structures with ALDAl₂O₃ films measured using three measurement schemes (a–c): (a) first measurement scheme; (b and c) second and third measurement schemes, respectively. *Inset:* measurement schemes for each specific case

between the mercury measuring probe and rhw Ohmic contact used is within 2.0–3.0 mm.

The aim of simulation using the three above-described measurement schemes is to find the optimum measurement scheme which would avoid the effect of collateral factors that can hinder the achieving of the specified task i.e., to study the effect of Al_2O_3 film deposition on the parameters of the dielectric/AlGaIn/GaN system.

The C–V characteristics were predominantly measured using a sequential (index “S”) substitution scheme.

3. Results and discussion

3.1. I–V measurements

Figure 1 shows the I–V characteristics obtained using the first measurement scheme for initial heterostructures grown on sapphire and SiC, as well as the results for heterostructures with oxide films measured using the second and third measurement schemes.

In heavy depletion regions, the measured currents (reverse branch) are the leakage currents I_{leak} which mainly characterize, in the case in question, the parameters of the barrier layer in the heterostructure. As can be seen from Fig. 1, the currents I_{leak} for the heterostructure on SiC are by one order of magnitude lower than those for the heterostructure on sapphire (10^{-10} and 10^{-9} A, respectively), which can be accounted for by the degree of the structural perfection of the epitaxial layers in those structures: the density of the sole through dislocations in the heterostructures grown on sapphire substrates is typically one order of magnitude higher than for the heterostructures on SiC [4].

As can be seen from Fig. 1, the formation of Ohmic contacts and Ni contact pads (Ni Schottky barriers) abruptly increases the leakage currents (by almost 2 orders of magnitude). This is expectable, since, for example, high-temperature annealing used for the production of Ohmic contacts and the presence of the Ohmic contacts themselves lead to the formation of a large number of free electrons in the bulk of the structures. As for the straight branch of the I–V characteristics, only if mercury probes were used, the I–V characteristics of nitride heterostructures had the shoulder K in the straight branch (see Fig. 1) showing that the flow of carriers in the channel is solely caused by thermal phonons. Upon a voltage shift towards higher values, at $+(2\text{--}2.5)$ V, the current grows dramatically due to electron emission to the conduction band. The I–V characteristics of the heterostructures after oxide film deposition exhibit a significant decrease in the leakage currents in the depletion region (by one order of magnitude, see Fig. 2a, Curves 1 and 2) as a result of surface passivation. After the deposition of thicker films, the region of lowest I_{leak} in the depletion region (the 2DEG channel region) shifts towards negative voltages. This is caused by the fact that part of the measurement bias

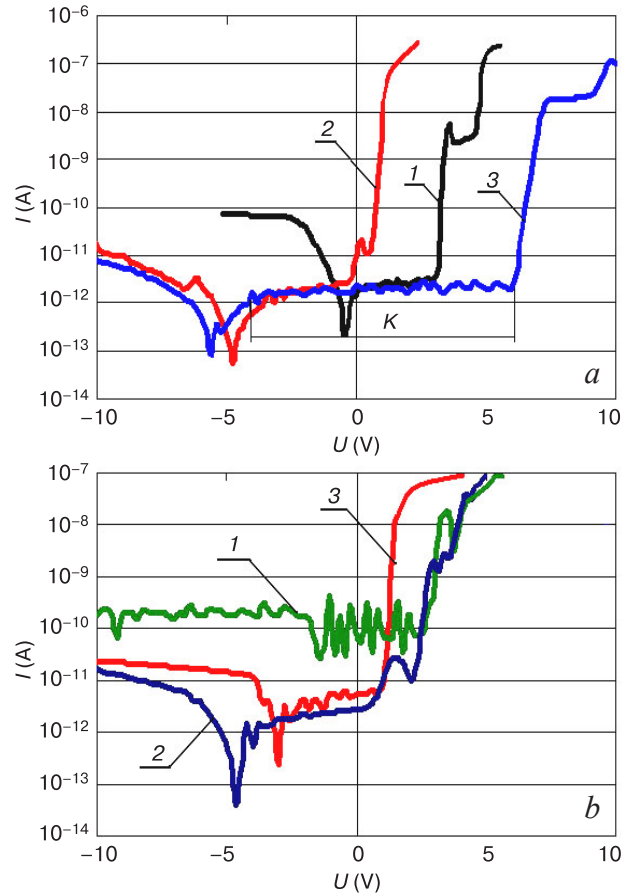


Figure 2. I–V characteristics of structures: (a) 1 and 3: with 20 and 40 nm Al_2O_3 films, respectively, 2: initial heterostructure; (b): 1: initial heterostructure, 2: heterostructure with 20 nm Al_2O_3 film, 3: after chemical removal of film

acts upon the oxide layer, while the other part affects the AlGaIn barrier layer (i.e., two capacitances in sequence form there). With an increase in the Al_2O_3 film thickness (to 50–60 nm), the length of the shoulder K increases, i.e., the voltage shifts towards positive values at which electrons are emitted to the conduction band (Fig. 2a, Curves 2 and 3). However, for 80–100 nm films, the electron emission to the conduction band is substantially suppressed. The ALD Al_2O_3 films can be easily removed chemically (with HF), and then the I–V characteristics shift towards positive values and their shapes become close to those of the I–V characteristics for the initial heterostructures, yet typically with lower leakage currents (Fig. 2b, Curves 1 and 3).

3.2. Capacity measurements

Figure 3 shows the measured capacity of the $\text{Al}_2\text{O}_3/\text{AlGaIn}/\text{GaN}$ system as a function of deposited aluminum oxide film thickness. The capacities of the films ($C_{\text{calc},\text{Al}_2\text{O}_3}$) are shown for different film thicknesses as calculated from the experimental total capacities of the deposited films and the barrier layers ($C_{\text{meas.}}$). The experimental capacities of the films were calculated using the conventional method for two sequentially connected ca-

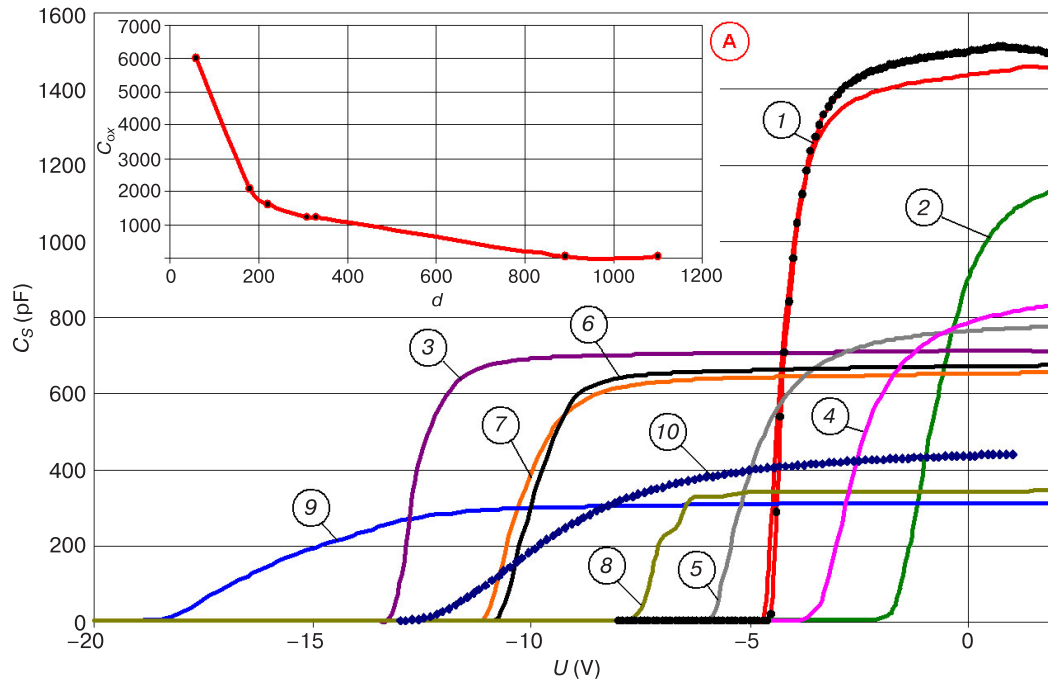


Figure 3. C–V characteristics of heterostructure specimens with Al_2O_3 films of different thicknesses: (1) initial heterostructure without film (2–10) heterostructures with films of different thicknesses of 10 to 120 nm. *Inset:* calculated film capacity as a function of film thickness

capacities ($1/C_{\text{meas.}} = 1/C_{\text{Al}_2\text{O}_3} + 1/C_{\text{AlGaIn}}$) [13]. The difference between the calculated and experimental capacities of the films ($C_{\text{Al}_2\text{O}_3} = (\epsilon_{\text{Al}_2\text{O}_3} \epsilon S)/d$, where $\epsilon_{\text{Al}_2\text{O}_3} = 9.5 \div 9.7$) was within 10 % (Fig. 3, Inset).

The overall capacity of the $\text{Al}_2\text{O}_3/\text{AlGaIn}/\text{Ga}$ system ($C_{\text{meas.}}$ is the flat section of the C–V curve) is quite a complex function of deposited film thickness (see Fig. 3), exhibiting a decrease in the capacity with an increase in the film thickness, especially for small film thicknesses (up to 25–40 nm). With a further growth of the film thickness, the growth of the overall system capacity decelerates sharply, and at film thicknesses of above 50–60 nm, the capacity changes little if any. Film thickness growth also leads to an increase in the cutoff voltage V_c from 3–3.5 to 17–31.8 V, suggesting an increase in the positive charge at the Al_2O_3 – AlGaIn boundary.

3.3. Charge in channel 2DEG and boundary electron states of $\text{Al}_2\text{O}_3/\text{AlGaIn}/\text{GaIn}$ system

Figure 4 shows carrier concentration (N) depth profiles in the structures calculated from the C–V curve [14] for three heterostructures with deposited Al_2O_3 films of gradually increasing thickness. The thinnest films were chemically removed after the measurements, and then new thicker films were deposited. For that concentration measurement scheme, the depth of the maximum carrier concentration corresponds to the overall thickness of the film and the AlGaIn barrier layer (counted from the channel to the barrier layer surface) for each specimen, i.e., in fact, N_{max} is, roughly, the carrier concentration in the channel 2DEG.

As can be seen from Fig. 4, film oxidation can cause charge redistribution in the channels of the structures, and, as a rule, a growth of the carrier concentration as a result of film deposition. After chemical removal of the film, the carrier concentration in the channel usually returns to its initial value (Fig. 4, Curve 1).

The density of electron states (the D_{it} distribution) at the boundaries of the $\text{Al}_2\text{O}_3/\text{AlGaIn}/\text{GaIn}$ system was estimated by means of capacity measurements with voltage sweep towards positive values in the process C–V measurements and computer-assisted processing of the experimental curves [3]. The bias range for most of the specimens was from $-(7 \div 5)$ V to $+(3 \div 5)$ V, i.e., beginning from $U = -(3 \div 1)$ V for direct bias, the capacity was almost constant and equal to the in-sequence capacity of the Al_2O_3 and AlGaIn layers (for 20–40 nm films). The latter curve section for measurements from $-(3 \div 1)$ V to $+(3 \div 5)$ V voltages exhibited an almost constant density of states at the AlGaIn – GaIn interface [3]. For the latter measurement scheme, the maximum possible bias was $+(5 \div 7)$ V, and later on, at the frequency $f = 1$ MHz, the capacity changed abruptly and in an uncontrolled manner. In the case in hand, the latter change was caused by an abrupt increase in the conductivity of the system, which was also observed earlier [3].

Taking into account the large time constant τ of AlGaIn [3, 9], the D_{it} distribution was initially studied as a function of measurement frequency. The experiments showed (Fig. 5a) that an increase in the measurement frequency from 10–50 kHz to 1 MHz for the same $\text{Al}_2\text{O}_3/\text{AlGaIn}/\text{GaIn}$ heterostructure caused a growth of the density of the observed donor-like shallow states by one order of

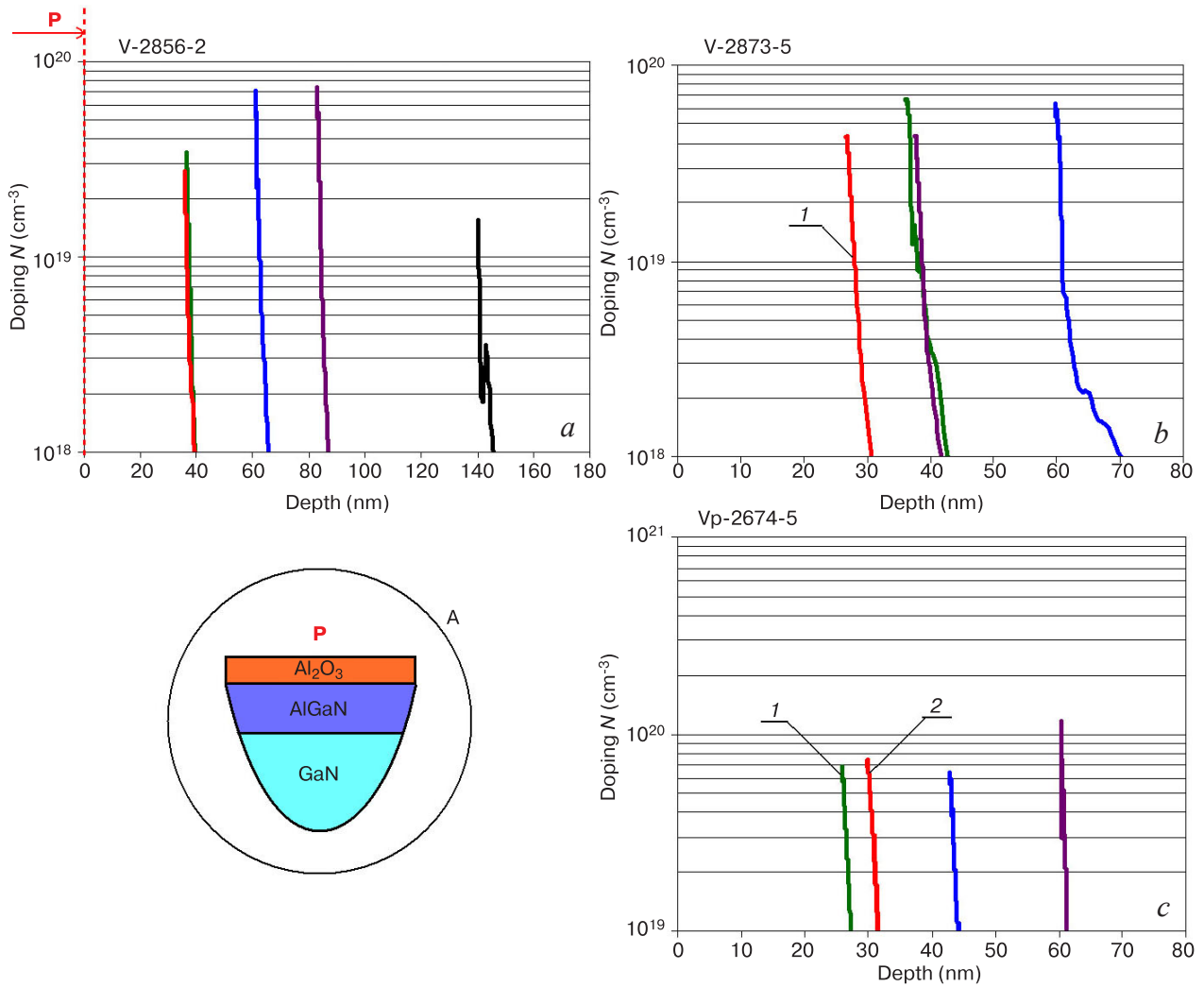


Figure 4. Carrier concentration depth profiles for three heterostructures (*a–c*) with Al₂O₃ films of different thickness: (1) after film removal, (2) initial heterostructure, and P is working surface of structures

magnitude and an abrupt increase in the density of the deep states.

Figure 5*b* (Region B) shows a graph of the D_{it} distribution obtained as a result of measurements at $f = 100$ kHz for the conventional heterostructure with a deposited Al₂O₃ layer (20 nm in thickness) superimposed with a graph of the $D_{it}(E)$ curve obtained earlier [3] at the same frequency for a similar structure with an ALD Al₂O₃ film of the same thickness. For most structures, the density of shallow level states measured at different frequencies was close to $1 \cdot 10^{12} - 1 \cdot 10^{13} \text{ cm}^{-2}$.

4. Discussion

Comparison between the three C–V characteristic three measurement schemes was required for a better understanding of the interface charging/recharging and current flow processes in a complex system such as Al₂O₃/AlGaIn/GaN. To obtain the required information from C–V measurements one should provide the overall capacity of the structure should be dominant by capacitive

component associated with a two-dimensional electron gas in the 2D channel. Analysis showed that the measurement scheme with two mercury probes (two Schottky barriers, see Fig. 1) which avoids any collateral technological influence provides for the minimum contribution from free carriers, e.g. from the metals of Ohmic contacts, and allows one to estimate the highest possible depletion degree of the 2DEG channel and to more accurately mark the start of electron emission to the channel (shoulder *K*). Furthermore, that measurement scheme allows judging, by the magnitude of the reverse current (I_{leak}), about the quality of the barrier layer in the initial heterostructure without high-temperature treatment, e.g. for the formation of Ohmic contacts. The latter advantage is of special importance for MIS and MOS transistor technologies since those currents (I_{leak}) exert direct effect on the controllability of the gate. Specifically, for the third measurement scheme (Ohmic contact/Hg Schottky barrier) (see Fig. 1), as well as for probe measurement on Ni contact pads (the second measurement scheme), even in the low reverse bias region, an increase in I_{leak} to 10^{-9} A can be associated with contact formation processes; e.g. during

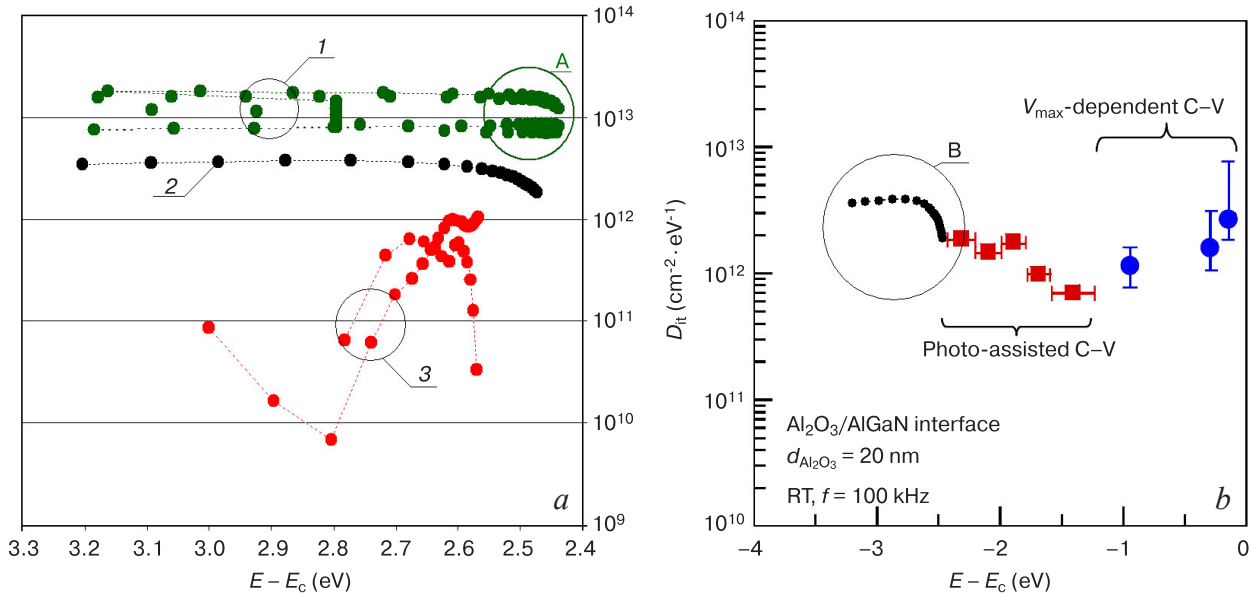


Figure 5. (a) D_{it} distributions of boundary states for a conventional heterostructure with a 20 nm Al_2O_3 film measured at different frequencies: (1) $f = 1$ MHz, (2) 100 kHz, (3) 10 kHz and (b) typical $D_{it}(E)$ distribution obtained at a measurement frequency of $f = 100$ kHz (Region B) and the characteristic $D_{it}(E)$ distribution obtained earlier [3] at the same frequency for a similar structure with a film of the same thickness

measurements of two metallic contact pads (see Fig. 1), the straight and reverse curve branches are always similar, as noted earlier by other researchers. The latter fact can be accounted for by the formation of a parasitic layer between the semiconductor surface and the nickel contact pad.

We will now dwell upon the problem of leakage currents during depletion. It was hypothesized earlier [13] that under heavy depletion conditions, the 2D electron gas of the $\text{AlGaIn}/\text{GaIn}$ structure, in fact, acts as a second electrode, and the applied voltage acts almost completely on the AlGaIn barrier layer, i.e., the measurements show the current of the carriers in the barrier layer, e.g. the effect of the traps in the layer. The latter approach is also justified if an oxide layer is present, thus allowing the current measured at a strong reverse bias to be considered a characteristic of applied voltage the structural perfection of the AlGaIn layer, although those charges can form either as states directly in the bulk of the barrier layer, or at the oxide/ AlGaIn interface, or even at the $\text{AlGaIn}/\text{GaIn}$ interface.

Based on analysis of the three above-described measurement schemes, we will hereinafter use the results of measurements conducted using the first measurement scheme, i.e., two mercury probes.

It is commonly believed that passivation can occur by two trap compensation mechanisms: by deep levels on the surface or in the bulk of the AlGaIn layer, by shallow donor-like levels at the dielectric/ AlGaIn interface, or by fixed positive charges at that interface [9, 15]. If the second mechanism takes place, the time constant is far less than that for shallow traps [15]. Furthermore, the dynamic parameters of the devices can vary depending on which of the mechanisms is activated [6, 15].

It is well-known [3, 8] that donor-like states remain neutral upon occupation with electrons, while acceptor-like ones acquire a negative charge upon the capturing of electrons. The latter negatively charged states at the oxide/ AlGaIn interface can screen the applied electric field during measurements, while in the HEMT transistors, the gate field suppresses the modulation of the AlGaIn potential [3]. The latter phenomena can cause a shift in the probe bias (or in the gates of transistors) towards positive values. Therefore, for shallow donor-like traps, the occupation rate of the dielectric/semiconductor interface states is a function of probe bias (or the gate voltage V_G for transistors).

During C-V measurements, an increase in bias to positive values ($U > +4$ V) shifts the potential of the AlGaIn layer to a plateau, thus triggering electron transfer from the $\text{AlGaIn}/\text{GaIn}$ interface to the $\text{Al}_2\text{O}_3/\text{AlGaIn}$ one (band diagram). If the applied bias shifts towards positive values, the Fermi level (E_F) can move in the AlGaIn band gap [14].

At a negative bias, the Fermi level is already located far below the AlGaIn valence band maximum at the $\text{Al}_2\text{O}_3/\text{AlGaIn}$ interface (band diagram) and, as a result, the electron occupation of the interface states is no longer a function of applied bias. It is not even always possible to completely deplete the channel ($I_{\text{chan}} > 10^{-12}$ A, Fig. 2b, Curve 1). A fixed charge is formed when the applied bias no longer controls the behavior of electrons at the interfaces.

Analysis of the experimental data showed that the ALD deposition of Al_2O_3 films leads to the formation of a positive charge at the interface, the charge magnitude growing with an increase in the film thickness (see Fig. 3). The latter assumption is testified to by the increase in

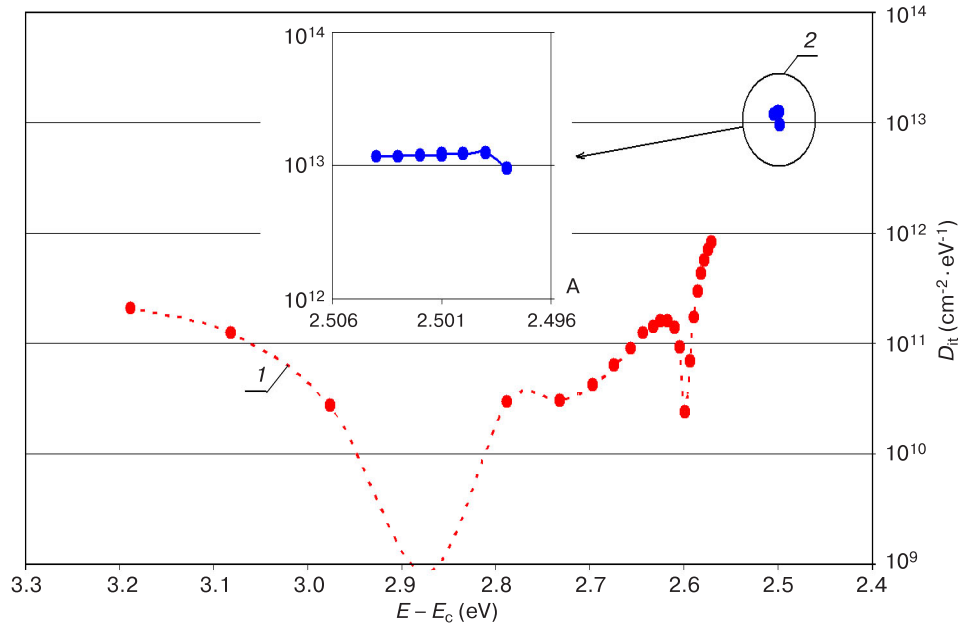


Figure 6. D_{it} distribution of boundary states obtained by measurements in hysteresis mode at $f = 10$ kHz for heterostructure with Al_2O_3 film (20 nm) at voltage sweep (1) from -9 to $+7$ V, (2) from $+8$ V to -7 V (inset A). *Inset:* magnified Curve 2

the shift of the bias voltage V_{th} towards negative values with an increase in the film thickness (see Fig. 3). Film deposition also affects the magnitude of the charge in the channel: typically, the charge increases after film deposition (see Fig. 4).

Correct treatise of the D_{it} energy distribution measurement results requires a number of determining factors be taken into account:

- as noted above, the applied electric field is split in three parts: between the oxide layer, the AlGaIn barrier layer, and the GaN buffer layer, thus complicating data treatise;
- due to the large time constant of electron emission for the abovementioned materials, estimation of electron emission from the system interfaces requires a strong bias [3]. However, in many cases, it is impossible to estimate the charge of deeper traps using conventional C–V measurements with simple biasing, because the measurement frequency also matters: charge transfer between boundaries may have not enough time to complete if the sweep frequency is high.

If the task is to estimate the D_{it} distribution, one should correctly take into account the C–V measurement frequency. The density of the detected shallow states increases with the measurement frequency, and those states are predominantly donor-like (see Fig. 5a, Region A, taking into account the Fermi level shift). As regards the deep acceptor-like states, the density of the detected states drops abruptly at low measurement frequencies (by two orders of magnitude, Fig. 5a).

Analysis of the obtained results suggests the following conclusions:

- during C–V measurements with a voltage sweep towards positive values, at a specific positive bias (in the

case in hand, $+5$ – 8 V), electron emission at the AlGaIn/GaN interface occurs, predominantly, from shallow donor-like centers (see Fig. 5a). With an increase in the bias towards positive values, electron emission from the AlGaIn/GaN interface triggers the formation of a negative charge at the oxide/AlGaIn interface (a shift of the U_{th} voltage towards positive values in the C–V curves), which compensates the positive charge whose magnitude increases with oxide film thickness (see Fig. 3);

- since analysis of the C–V measurement results for structures with deposited oxide films also suggests an increase in the carrier concentration in the channel (see Fig. 4), it is safe to state that some of electrons remain in the channel upon recharging at the $\text{Al}_2\text{O}_3/\text{AlGaIn}/\text{GaN}$ system interface.

As regards the electrons that could be captured at the states near the oxide/AlGaIn interface, the question is whether electron emission from that interface, e.g. to the channel, is possible.

In our opinion, the latter can be judged about by taking into account possible recharging during the measurements in hysteresis mode at reverse voltage sweep from positive to negative values, e.g. from $+8$ V to -5 V. At a 10 kHz frequency, the D_{it} distribution shown in Fig. 6 was obtained. Electron emission from shallow donor-like levels at the $\text{Al}_2\text{O}_3/\text{AlGaIn}$ interface was observed (Fig. 6, Curve 2).

In our opinion, the measurements carried out in this work show that the problem of boundary electron states in the dielectric/AlGaIn/GaN system (their configuration, charging/recharging processes, and effect on device operation) is complex and requires further investigation, especially for film synthesis using advanced high-tech processes such as ALD.

Conclusion

It was found that the C–V measurement scheme with two planar mercury probes on the dielectric surface is the optimum one for the correct understanding of interface charging/recharging and current flow processes in the 2DEG channel for complex systems such as dielectric/AlGaIn/GaN. It was shown that ALD deposition of an Al₂O₃ film leads to the formation of a positive charge at the oxide/AlGaIn interface, the magnitude of which grows with an increase in the film thickness. Furthermore, it was shown that film deposition affects the charge in the channel. Experimental data were obtained on the

role of the frequency at which the C–V measurements are carried out for the estimation of D_{it} distribution at Al₂O₃/AlGaIn/GaN system interfaces. Analysis of the C–V characteristics showed that carrier emission from the oxide/AkGaIn interface can occur in such systems.

ALD Al₂O₃ films with a thickness of 10–50 nm proved to be the most stable.

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