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doi:10.15199/48.2025.02.37

Buffer leakage current in lateral AlGaN/GaN HEMT

***Abstract**. The current leakage through the buffer layer in AlGaN/GaN type HEMT (High Electron Mobility Transistor) is an important factor for creating semiconductor AIIIN based devices with predictable parameters. In this study the current flow and potential distribution in AlGaN/GaN heterostructures with two conducting channels and a buffer layer are investigated. The presence of the second conducting channel has a significant impact on the current flow, especially in the case of unintentionally doped semi-insulating GaN buffer layers or in the presence of a strong electric field.*

Streszczenie.** Upływ prądu przez warstwę buforową w tranzystorach HEMT typu AlGaN/GaN jest istotnym czynnikiem w wytwarzaniu elementów półprzewodnikowych na bazie materiałów z grupy AIIIN, o zadanych parametrach. W pracy przeanalizowano przepływ prądu i rozkład potencjału w heterostrukturach AlGaN/GaN z dwoma kanałami przewodzącymi i warstwą buforową. Obecność drugiego kanału przewodzącego ma znaczący wpływ na przepływ prądu, szczególnie w wypadku nieintencjonalnego domieszkowania półizolacyjnych warstw buforowych GaN lub w obecności silnego pola elektrycznego. (**Prąd upływu bufora w lateralnym tranzystorze AlGaN/GaN HEMT)

Keywords: Buffer, AlGaN/GaN, HEMT, current leakage.
Słowa kluczowe: Warstwa buforowa, AlGaN/GaN, HEMT, prąd upływu

Introduction

The intensive research on HEMT transistors starts in 1980 by T. Mimura who published article entitled ”A new field-effect transistor with selectively doped GaAs/n-AlxGa1−xAs heterojunctions”. Initially, HEMT transistors were fabricated in AIIIBV semiconductors, mostly GaAs. Nowadays the AIIIN materials like GaN due their unique properties are also applied for this purpose [1]. AIIIN piezoelectric materials offers higher efficiency and lower power consumption [2–4]. AlGaN/GaN heterostructures of the HEMT type are commonly grown using the metal-organic vapor phase epitaxy (MOVPE) technique with the AIXTRON CCS (Close Coupled Showerhead) system [5-7]. The characteristic feature of AlGaN/GaN heterostructures is a presence of the 2DEG conductive channel as a result of the charges induced by spontaneous and piezoelectric polarization [8, 9] combined with the donor surface states [10, 11] without any additional n-type doping of AlGaN layer. The donor surface states [8, 12] involved in the creation of 2DEG also acts like virtual gate that reduces the drain current [11]. Moreover the energy levels on the surface are located in the forbidden energy gap [13] that could also cause the gate-lag and drain-lag [14]. In the operation of AlGaN/GaN type HEMT transistors an important role for maintain the carriers in the 2DEG channel plays the high-resistive gallium nitride buffer fabricated during MOVPE process by unintentionally carbon atoms doping originating from metalorganic reagents. The carbon atoms behaved as deep energetic centers and are the main factor preventing the current leakage. However, an excessive concentration of carbon atoms can negatively impact the parameters of transistors operating as switches [15–17]. Furthermore, the strong electric field associated with AlGaN/GaN HEMT transistors introduces a self-heating effect [18] and in low insulating GaN buffers the carriers from the 2DEG channel are pushed into the bulk layer or surface states.

Electrons in the quantum well are injected into the bulk GaN layer and occupy deep energy levels formed by unintentionally introduced carbon atoms during MOVPE process. As a result, AlGaN/GaN HEMT transistors fabricated in such heterostructures exhibit a phenomenon known as ”current collapse” where the drain current decreases as the source-drain voltage increases [19]. Ensuring the proper flow of current in AlGaN/GaN heterostructures is currently a subject of interest for many researchers the aim is to create a buffer layer with the highest possible resistivity that not affect the 2DEG conduction in high electric fields. Currently, achieving high resistivity in the GaN layer is also possible by using Fe atoms as dopants (primarily in MBE reactors). These dopants as well the carbon atoms effectively compensate the residual donor impurities (such as Si and O). The use of Fe in MOVPE reactors can lead to reactor contamination due to the introduced impurity and the strong memory effect, where iron atoms diffuse into the adjacent active region. In the case of intentional doping of the GaN layer with carbon atoms, obtaining a highly resistive gallium nitride layer is challenging due to the self-compensation effect [20]. The AlGaN/GaN heterostructures, with additional parasitic conducting channel, during Hall measurements exhibits averages electrical properties due to current leakage through semi-insulating GaN buffer layer [21, 22].

Additionally, to study the buffer current leakage of AlGaN/AlN/GaN type HEMT heterostructure, the simulations of conduction of two channels and semi-insulated buffer layer of varied thickness are perform.

AlGaN/AlN/GaN:n+ type HEMT heterostructures

A three-dimensional AlGaN/GaN/GaN:n+ heterostructure with two conducting layers is shown in Figure 1. The first conducting layer consists of a 2DEG channel with a concentration of n_{2D} and mobility μ_{2D}, while the second conducting layer is intentionally doped n-type layer with a concentration of n_{3D} and mobility μ_{3D}.

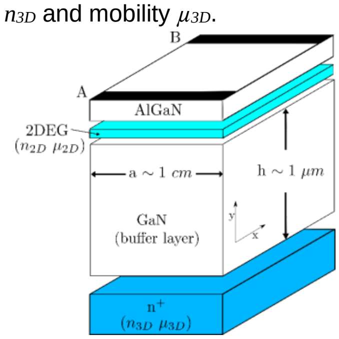

Fig. 1. Three-dimensional schematic of an AlGaN/GaN/GaN:n+ heterostructure with two conducting channels

Between the conducting channels, there is an undoped GaN layer with a height h equal to 1 *μm* and a width of 1 cm. A simplified schematic of the AlGaN/GaN heterostructure with two conducting channels and a GaN buffer layer is shown in Figure 2.

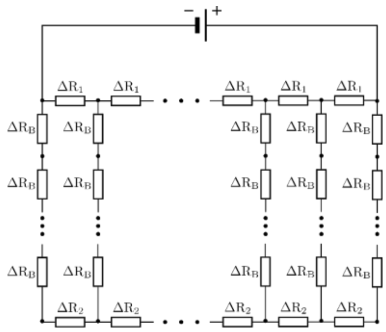

Fig. 2. Simplified schematic of the AlGaN/GaN/GaN:n+ heterostructure with two conducting channels and a GaN buffer layer

The first and second conducting channels are represented as a series of resistances ΔR_1 and ΔR_2 respectively. The GaN buffer layer consists of a series of resistances ΔR_B. An external voltage is applied to the contacts on the top of the AlGaN/GaN/GaN:n+ heterostructure. As a result, a current will flow through the AlGaN/GaN/GaN:n+ heterostructure through two conducting channels accordingly to the Kirchhoff's first law. The current in the first conducting channel is I_1, in the GaN buffer layer I_B and in the second conducting channel I_2. At a distance of $L = \infty$ from the top contact, the currents I_1 and I_2 will have constant values due to the current flowing through the GaN buffer layer equals $I_B = 0$. Additionally, the potentials in both channels in the central part will be the same, $U_1 = U_2$ and due to symmetry of the heterostructure equals zero, $U_{10} = U_{20} = 0$. See Figure 3 for reference.

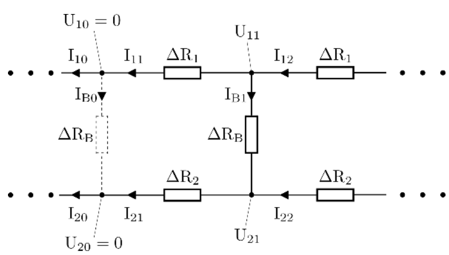

Fig. 3. The current distribution in the AlGaN/GaN/GaN:n+ heterostructure with two conducting channels at a distance $L = \infty$ from the contact

Expressing the voltage drops in the first and second conducting channels as infinitesimal increment of resistances, $U_{10} = I_{10}\Delta R_1$ and $U_{20} = I_{20}\Delta R_2$, the following initial conditions in the middle part of the heterostructure are as follows:

$$U_{10} = U_{20}$$
$$\frac{I_{10}}{I_{20}} = \frac{R_{s2}}{R_{s1}} \tag{1}$$

where, the infinitesimal increment of resistances in the 2DEG channel and the n-type doped GaN layer can be expressed by the surface resistances, R_{s1} and R_{s2}:

$$\Delta R_1 = R_{s1}\frac{dx}{a}, \qquad \Delta R_2 = R_{s2}\frac{dx}{a}$$

here the dx is an element of length along the x axis of the heterostructure, as shown in Figure 1.

Based on Figure 3, the first and the second Kirchhoff's laws in each node of the analyzed AlGaN/GaN/GaN:n+ heterostructure can be expressed as:

$$I_{11} = I_{10} + I_{B0}$$
$$U_{11} = U_{10} + I_{11} \cdot \Delta R_1$$
$$I_{21} = I_{20} - I_{B0} \tag{2}$$
$$U_{21} = U_{20} + I_{21} \cdot \Delta R_2$$
$$I_{B1} = \frac{U_{11} - U_{21}}{R_B}$$

where I_{11} and I_{21} are the currents in the first nodes of the first and second conducting channels. The current flowing through the GaN buffer layer at node I_{B1} is defined as the ratio of the voltage drops in the first and second channels U_{11} and U_{21}, respectively, to the resistance value R_B of the GaN buffer layer. The buffer resistance R_B itself is equals to $R_B = n\Delta R_B$, where n is the number of resistive elements across the buffer layer. The infinitesimal increment of resistance in the buffer layer is defined as follow:

$$\Delta R_B = \rho_B \cdot \frac{dh}{dx \cdot a} \tag{3}$$

where dh is a small change in the height of the heterostructure, given by $dh = h/n$, and ρ_B is the resistivity of the buffer layer, that depends on the concentration and mobility of electrons in the layer:

$$\rho_B = \frac{1}{e \cdot n_B \cdot \mu_B} \tag{4}$$

Substituting $dh = h/n$ and $\Delta R_B = R_B/n$ into equation 3, the resistance of the GaN buffer layer is equal:

$$R_B = \rho_B \frac{h}{dx \cdot a} \tag{5}$$

Moving away from the middle part of the heterostructure by a small distance dx, the currents I_1 and I_2 will start to change. The current in the first branch, I_1, will increase, while the current in the second branch, I_2, will decrease. To satisfy this condition the initial value of I_B have to be nonzero and current in the upper branch is incremented by a value of $\Delta I > 0$, where $\Delta I << 0\ I_{10}$. In the considered model, the current flow occurs through the conducting channels and the buffer layer only. Therefore, the current in the lower channel, in the middle part of the heterostructure, have some additional initial conditions, e.g., $I_{20} = 0{,}1$ mA.

$$I_{10} = I_{10} + \Delta I \tag{6}$$

$$I_{20} = 0.1\ mA$$

Near the contact point where electric charges are injected, the current value in the second conducting channel will be zero, while the current flowing through the buffer layer has maximum value.

Results

The current flows in the AlGaN/GaN/GaN:n+ heterostructure with two conducting channels are shown in Figure 4. Carrier injection occurs at $x = 0$. The currents flowing in the upper I_1 and lower I_2 conducting layers will reach their steady-state values for $x > 3\ mm$ when current leakage through the buffer layer I_B is negligible.

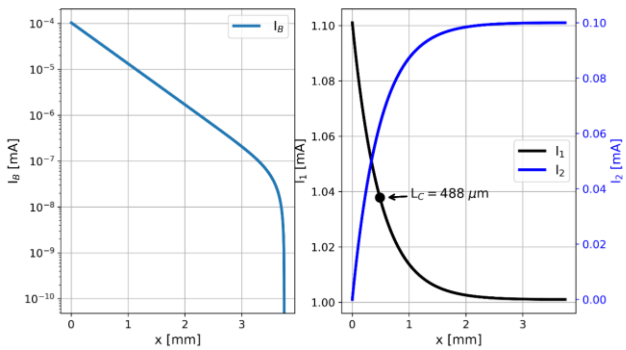

Fig. 4. The current I_B flowing through the semi-insulating GaN (left side), the current I_1 flowing in the first conducting channel, and the current I_2 flowing in the second conducting channel (right side) as a function of the position x. L_C represents the convergent length, which is the distance at which the current in the first conducting channel decreases e-times compared to it's initial value

At a distance of the convergent length $L_C = 488$ µm from the carrier injection point, the current in the first conducting channel decreases e-times compared to it’s initial value. In the considered AlGaN/GaN/GaN:n+ heterostructure, the surface resistance of the first conducting channel is equals $R_{s1} = 400$ Ω/sq, which is a typical value obtained from Hall effect measurements at a temperature of 300 K [22], the surface resistance of the second conducting channel is defined as $R_{s2} = 4000$ Ω/sq and the resistance of the buffer layer at the distance dx is 4166 Ω. To satisfy the initial conditions from equation 6 and 1, the initial value of the current in the second channel is equal $I_{20} = 0{,}1$ mA and the initial value of the current in the first channel is equal $I_{10} \approx 1 + 0{,}001 = 1{,}001$ mA respectively.

In the next stage, the current flow in the first conducting channel I_1 was studied as a function of the distance from contact A and the buffer layer thicknesses changed from 0.25 µm to 2 µm, the results are shown in Figure 5. The thickness of the semi-insulating buffer layer significantly affects the value of the convergent length, L_C, changing from 346 µm for thin buffers of around 0.25 µm to 689 µm for 2 µm thick buffers.

Increasing the thickness of the GaN buffer layer h_B the resistance over the distance dx become larger. As a result, the current flow through the buffer I_B decreases and the convergent length L_C extend. The final value of the current in the first conducting channel I_1, is independent of the thickness of the GaN layer. However, the distance required to reach this value increases with the thickness of the buffer. The potential in the first and second conducting channels as a function of the distance from contact A is shown in Figure 6. The largest potential difference occurs at the carrier injection point, where the potential in the first conducting channel is approximately 3.05 mV , while in the second channel, it is approximately 2.6 mV. The potential in the first conducting channel is linear, while in the second conducting channel nonlinear. On figure the distances L_C, represent point where the current in the first conducting channel decreases e-times compared to its initial value.

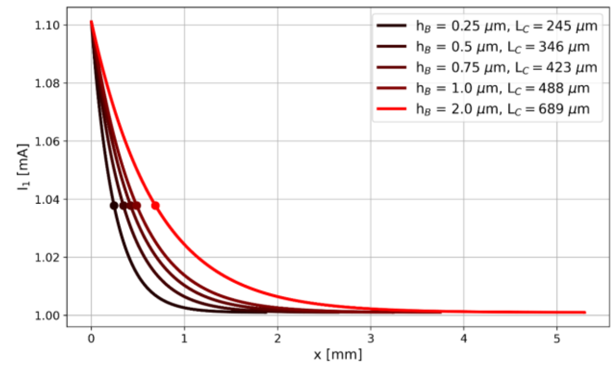

Fig. 5. The current flow in the first conducting channel I_1 as a function of the distance from contact A and buffer layer thickness ranging from 0.25 µm to 2 µm as parameter

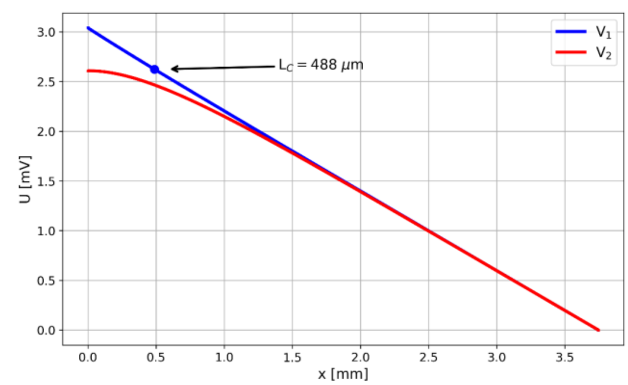

Fig. 6. The potential in the first and second conducting channels as a function of the distance from the contacts.

In the process of metal-organic vapor phase epitaxy (MOVPE), high-resistivity GaN layers are often grown using unintentional doping from the metal-organic compounds in the MOVPE reactor. The insulation of the GaN layer can also change during the operation of high-electron-mobility transistors (HEMTs), where electrons from the 2DEG channel are pushed into the buffer. In further investigations, the electron concentration in the buffer layer takes values of $n_B = 1{\cdot}10^{13}$ cm^{-3}, $n_B = 2{\cdot}10^{13}$ cm^{-3} and $n_B = 3{\cdot}10^{13}$ cm^{-3}, while the electron mobility was constant and equals 150 cm^2/V · s. In results, over the distance dx, the resistances of the buffer layer was 4166 Ω, 2083 Ω and 1388 Ω, respectively. The current in the first and second conducting channels as a function of the distance from contact A for different values of the buffer layer resistance is shown at Figure 7.

The increase in electron concentration in the buffer directly decreases it’s resistance, leading to a reduction in the convergent length L_C . The value of the current in the second conducting channel strongly depends on the current flowing through the buffer, I_B. The relationship of current leakage through buffer as well the potentials in the first and second conducting channels with an electron concentration in buffer as a parameter is shown at Figure 8.

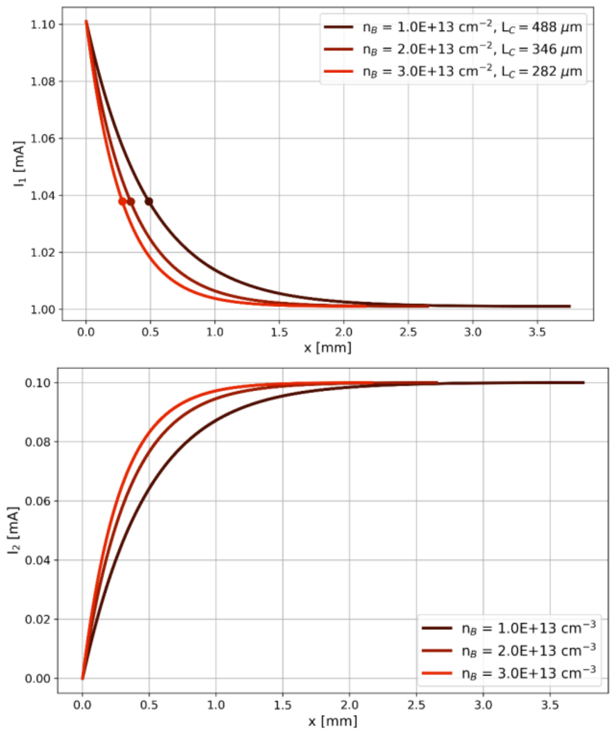

Fig. 7. The current in the first and second conducting channels as a function of the distance from contact A for electron concentrations in the buffer layer: $n_B = 1{\cdot}10^{13}$ cm^{-3} (top), $n_B = 2{\cdot}10^{13}$ cm^{-3} and $n_B = 3{\cdot}10^{13}$ cm^{-3} with a constant electron mobility equals 150 cm^2/V · s (bottom)

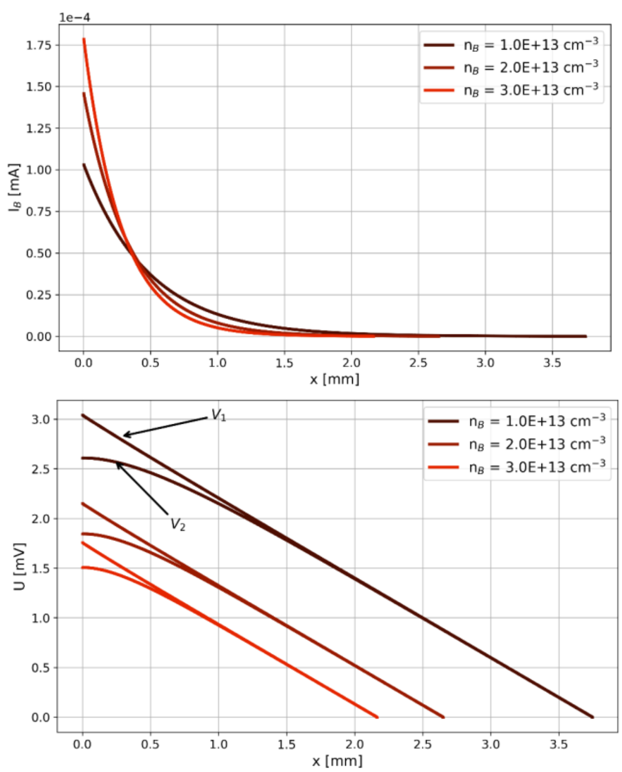

Fig. 8. The current in the first and second conducting channels as a function of the distance from contact A for electron concentrations in the buffer layer: $n_B = 1{\cdot}10^{13}$ cm^{-3}, $n_B = 2{\cdot}10^{13}$ cm^{-3} (top) and $n_B = 3{\cdot}10^{13}$ cm^{-3} with a constant electron mobility equals 150 cm^2/V · s (bottom)

The analysis of current flow through the buffer layer reveals that the presence of the second conducting channel significantly affects the current distribution in the AlGaN/GaN heterostructure. Particularly in the areas where the gallium nitride buffer layer becomes semi-insulating due to unintentional doping or in the presence of a strong electric field.

Conclusion

The current flow and potential distribution in AlGaN/GaN heterostructures with two conducting channels and a high resistive buffer layer is studied. It is concluded that the resistance of the buffer layer is a key factor for distribution of the currents in conduction channels with a predictable convergent length. In the presence of current leakage through the semi-insulating buffer layer the second conducting channel significantly affects the current in 2DEG channel in the AlGaN/GaN heterostructure. This also has an relevant impact in the results obtained by Hall measurements in AlGaN/GaN heterostructures with parasite conducting channel.

Acknowledgments: *The research was co-financed by the National Science Centre under the projects MINIATURA 2024/08/X/ST7/00040 and OPUS 2022/45/B/ST5/04292, the National Agency for Academic Exchange under the contract BPN/BSK/2023/1/00040/U/00001 and Wroclaw University of Science and Technology subsidy. Maintenance of the research infrastructure was financed under the Ministry of Education and Science project No. 36/564935/SPUB/SP/2023. The research was accomplished thanks to the product indicators and result indicators achieved within the framework of the projects co-financed by the National Centre for Research and Development under TECHMATSTRATEG project No. 1/346922/4/NCBR/2017.*

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