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The Origin and Influence of Compensatory Current in AlGaN/GaN Type High Electron Mobility Transistor Heterostructures with Two Conducting Channels on the Hall Measurements

Mateusz Glinkowski, Bogdan Paszkiewicz, Mateusz Wośko, and Regina Paszkiewicz*

The second conducting channel is created in AlGaN/GaN type high electron mobility transistor (HEMT) heterostructures deposited by the metal organic vapor phase epitaxy (MOVPE) technique, in which the pressure changes during the growth of the buffer GaN layer to ensure its high resistivity. It is stated that a second, parasitic, conducting channel is induced as a result of nonintentional doping that occurs at the GaN–GaN interface. The Hall measurements, in the wide range of temperatures, from 77 to 420 K, are used to obtain sheet resistivity, sheet carrier concentration, and electron mobility of the heterostructures. The theoretical model of the multilayer transport in AlGaN/GaN type HEMT heterostructures, based on an equivalent circuit, allows for estimation of compensatory current. Based on the theoretical model, the correction map for the Hall measurement of the samples with two conducting channels is evaluated. The measured electron mobility μ_{meas} obtained from Hall measurement is applied for the determination of the 2D electron gas (2DEG) mobility μ_1 of the samples with two conducing channels using the equation $\mu_1 = \alpha\mu_{meas}$. It is observed that the appropriate correction coefficient α depends on second channel parameters, i.e. the sheet resistance and mobility of the second conducting channel.

1. Introduction

Since 1980, high electron mobility transistors (HEMTs) based on classical AIIIBV have been the subject of the intense research.[1] However, a complete understanding of the operation of AlGaN/GaN HEMTs is still unknown. Eller et al. and Ibbetson et al.[2,3] showed that the surface states are involved in the creation of the 2D electron gas (2DEG). In contrast, surface states act like a virtual gate that reduces the drain current.[4] Energy levels on the surface located in the energy bandgap[5] will influence the gate lag and drain lag.[6] During the growth of high resistive gallium nitride buffer layers by the metal organic vapor phase epitaxy (MOVPE) technique, carbon atoms from metal organic reagents behaved as deep energetic centers and is the main reason for current leakage.[7–9] A strong electric field associated with the operation of AlGaN/GaN HEMTs caused the self-heating of the HEMT channel[10] and could inject carriers from the 2DEG channel to surface states or to the bulk. Electrons injected to the bulk fill deep energetic trap levels could also lead to a current collapse effect observed in AlGaN/GaN HEMTs.[11]

Many different methods enabled the characterization of the AlGaN/GaN type HEMT heterostructures. One of them is the classical measurement of the Hall effect,[12] that in pair with the measurement of sheet resistance $R_s(\Omega\,\mathrm{sq}^{-1})$ carried out using the van der Pauw method[13] allows to determine the 2DEG mobility, μ_{2DEG} ($\mathrm{cm^2\,V^{-1}\,s^{-1}}$), and sheet electron concentration n_s ($\mathrm{cm^{-2}}$). During the Hall measurements, the longitudinal and transverse galvanic-thermomagnetic effects are present. Effects, such as Seebeck, Nernst, Ettingshausen, and so on, are described in many previous studies.[14,15] The additional effect that could be observed in the Hall temperature measurement is related to the compensatory current flow in transistor structures with a parasitic second channel that occurred as a result of the pressure modification during the growth of the high resistive buffer of the AlGaN/GaN type HEMT heterostructures. Due to the different electrical parameters of individual channels, after applying a perpendicular magnetic field, in each channel a different value of the electromotive force (EMF) will occur.

It is observed in Hall temperature measurements carried out on both types of samples that the second conducting channel was formed in AlGaN/GaN type HEMT heterostructures where the high resistive buffers were fabricated in four stages using different pressures during the MOVPE process. It is also observed that in this case, the values of sheet electron concentration increased and 2DEG mobility decreased. It is assumed that the second conducting channel results from nonintentional doping during the epitaxy process.[16] The mobility of electrons in the second conducting channel and their concentration can be estimated using classical Hall measurements carried out in a wide temperature range.

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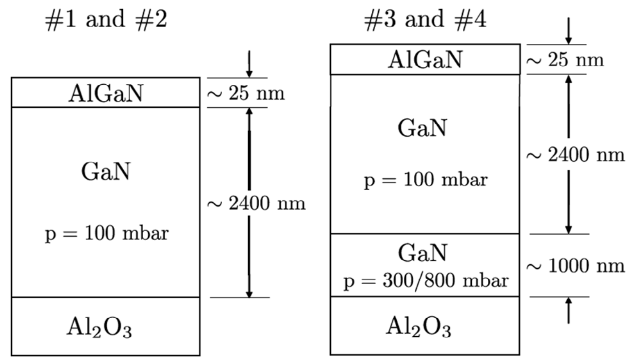

Figure 1. Reference AlGaN/GaN type HEMT heterostructures (left) and AlGaN/GaN type HEMT heterostructures grown with pressure modification (right) on sapphire substrates. The pressure in samples #1 and #2 is 100 mbar, whereas in sample #3, it is 300 mbar, and in #4, it is 800 mbar.

2. Experimental Section

The AlGaN/GaN type HEMT heterostructures were grown by the MOVPE technique using the AIXTRON FT CCS system. Prior to material growth, a 2 in., *c*-plane sapphire substrate (Al_2O_3) was thermally cleaned for 10 min at 1100 °C in hydrogen atmosphere and subsequently, the sapphire surface was treated with NH_3 at 540 °C for 3 min. An low temperature (LT) GaN nucleation layer (40 nm thick) was deposited, in H_2 atmosphere, at a pressure of 100 mbar using TMGa and NH_3 precursors.[17] In the next step, the high resistive buffer GaN layer for samples #1 and #2 was grown at 100 mbar at 1060 °C. In the case of samples #3 and #4, the growth process of the GaN high resistive buffer layers consists of four phases: increasing the pressure to 300/800 mbar, deposition of the first 1000 nm GaN layer, return to 100 mbar pressure, and subsequent growth of the second 2000 nm GaN layer. On top of the GaN buffer, the AlGaN layer was deposited, at 1060 °C, that consisted of an undoped 1.66 nm AlN, undoped 5 nm AlGaN, silicon-doped 15 nm AlGaN with Si concentration of 10^{18} cm^{-3}, and undoped 5 nm AlGaN followed by 2 nm AlN cap. **Figure 1** shows simplified AlGaN/GaN type HEMT heterostructures grown by the MOVPE method. The influence of pressure on 2DEG mobility and sheet electron concentration in AlGaN/GaN type HEMT heterostructures was observed. However, during the epitaxy process, many additional important factors like interruption and continuation of the deposition, heating the deposited layer, and switching the pressure time should also be considered to appropriate the investigation of the origin of parasitic channel formation.

3. Theoretical Model

The simplified 3D model and current flow in AlGaN/GaN type HEMT heterostructures with pressure modification during the high resistive buffer growth is shown schematically in **Figure 2**. The model of the examined heterostructure consists of three layers: the AlGaN spacer with an Al content of 25%, the 2DEG layer with electrons in a triangular quantum well, and the GaN layer that represents the second conducting channel formed in the high resistive GaN buffer layer.

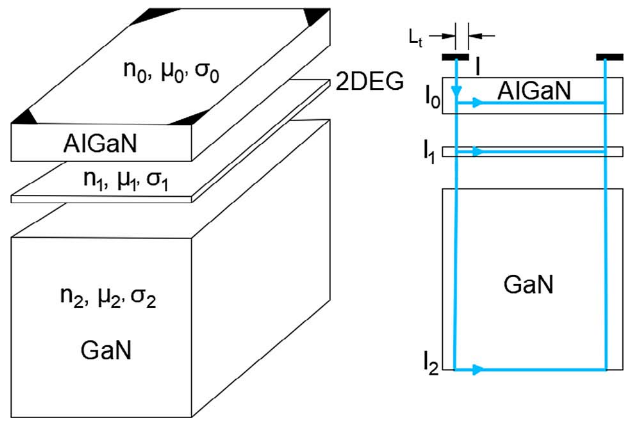

Figure 2. The simplified 3D model (left) and current flow (right) in AlGaN/GaN type HEMT heterostructures grown with the pressure modification in the MOVPE process. The electron mobility, electron concentration, and electron conductivity are different in each layer. The path of the current flow through the channels in AlGaN (I_0), 2DEG (I_1), and GaN (I_2). L_T is the transfer length of the current crowding.

3.1. Multilayer Transport in AlGaN/GaN Type HEMT Heterostructures

The current I that flows from the source to drain spreads simultaneously between the channels. In the AlGaN, 2DEG, and GaN channels the current I_o, I_1, and I_2 will flow, respectively. Each of layer has unique electrical properties such as electron concentration n, electron mobility μ, and electron conductivity σ. Charge compensation in AlGaN/GaN type HEMT heterostructures depleted the carriers in the AlGaN layer, and the carriers in the AlGaN layer are a part of the 2DEG.[3] Consequently, there is no current in the AlGaN layer which means $I_0 = 0$. Therefore, in the case, when the resistance between two others channels is relatively low, a connection between 2DEG and GaN channels exists. Without the presence of a magnetic field, the current flow is shown in **Figure 3**.

In AlGaN/GaN type HEMT heterostructures grown with pressure modification, the difference in electron mobility and electron concentrations between channels will result in different EMFs[18] when the magnetic field is applied. The dissimilarity in EMF will result in the flow of the compensatory current, J_c. The equivalent circuit of such AlGaN/GaN type HEMT heterostructures in the magnetic field is shown in **Figure 4**.

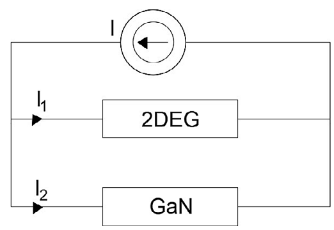

Figure 3. The current flow model in the AlGaN/GaN type HEMT heterostructures grown with the pressure modification of the MOVPE process without the presence of magnetic field.

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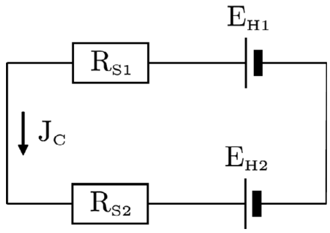

Figure 4. An equivalent circuit of the current flow between the channels in AlGaN/GaN type HEMT heterostructures grown with the pressure modification of the MOVPE process in the presence of a magnetic field.

where R_{s_i} is the sheet resistance for each channel[19]

$$R_{s_i} = \frac{1}{en_i\mu_i}(\Omega\,\mathrm{sq}^{-1}) \tag{1}$$

and i is number of the channel.

Assuming that electrons possess the same velocity v_x and the magnetic field is perpendicular to the electron current flow, the Hall electric field completely compensates the Lorentz force according with the equation $E_\mathrm{H} = v_x B_z$.[15] In the low electric field regime, the drift electron velocity is proportional to the electric field $v_x = \mu_\mathrm{meas} E_x$,[20] where μ_meas is the measured mobility in the Hall experiment. Then the Hall electric field can be expressed as

$$E_\mathrm{H} = \mu_\mathrm{meas} E_x B_z (\mathrm{mV\,mm^{-1}}) \tag{2}$$

Based on Figure 4, the equation that describes the compensatory current flow in the pressure-modified AlGaN/GaN type HEMT heterostructure in the magnetic field is

$$E_\mathrm{H1} - E_\mathrm{H2} - J_\mathrm{c} R_{s_1} - J_\mathrm{c} R_{s_2} = 0 \tag{3}$$

where $E_\mathrm{H1} = \mu_1 E_x B_z$ and $E_\mathrm{H2} = \mu_2 E_x B_z$ are the Hall fields in the first and the second channels, respectively. The electric field in the x direction, E_x, is associated with the linear current density, J_x, in the same direction and the sheet resistances of parallel channels.

$$E_x = \mathrm{J}_x\left(\frac{R_{s_1}\cdot R_{s_2}}{R_{s_1}+R_{s_2}}\right)(\mathrm{mV\,mm^{-1}}) \tag{4}$$

In addition, it is assumed that EMF of the first channel is greater than that in the second one. The compensatory current is therefore

$$J_\mathrm{c} = \frac{E_\mathrm{H1}-E_\mathrm{H2}}{R_{s_1}+R_{s_2}}(\mathrm{mA\,mm^{-1}}) \tag{5}$$

The compensatory current as the function of sheet resistance of the second channel with the linear current density in x direction as the parameter is shown in **Figure 5**; the data used in the calculation are shown in **Table 1**.

3.2. Correction Coefficient and 2DEG Mobility

The correction coefficient α is a factor between 2DEG mobility μ_1 and the measured electron mobility μ_meas

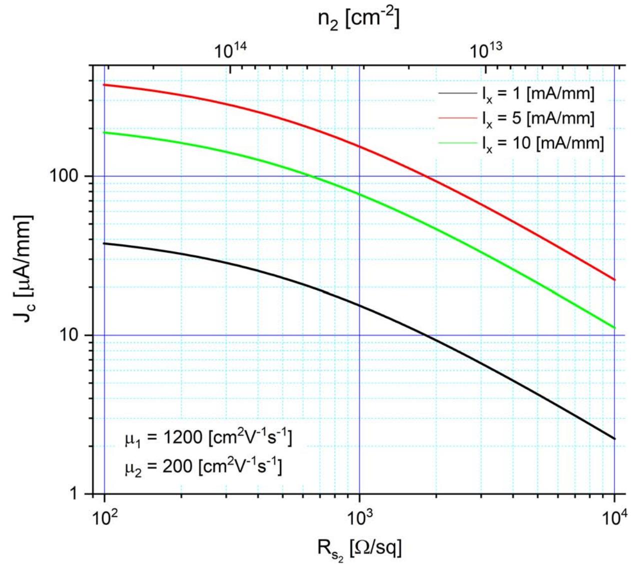

Figure 5. The compensatory current in the function of sheet resistance in the second channel. The data used for calculation are shown in Table 1.

Table 1. Data used for calculating the compensatory current (Figure 5).

Quantity	Value	Unit
Magnetic field in z direction	$B_z = 0.524$	T
2DEG mobility	$\mu_1 = 1200$	$\mathrm{cm^2\,V^{-1}\,s^{-1}}$
Electron mobility in the second channel	$\mu_2 = 200$	$\mathrm{cm^2\,V^{-1}\,s^{-1}}$
2DEG concentration	$n_1 = 10^{13}$	$\mathrm{cm^{-2}}$
Linear current density (parameter)	$J_x = (2, 5, 10)$	$\mathrm{mA\,mm^{-1}}$

$$\alpha = \frac{\mu_1}{\mu_\mathrm{meas}} \tag{6}$$

Analyzing Equation (6), 2DEG mobility μ_1 can be determined by multiplying the measured electron mobility μ_meas by the correction coefficient α.

The measured Hall electric field is equal to the Hall electric field and voltage drop in each channel

$$E_\mathrm{H} = E_\mathrm{H2} + J_\mathrm{c} R_{s_2} \tag{7}$$

Substituting Equation (5) into Equation (7), the measured Hall electric field is

$$E_\mathrm{H} = E_\mathrm{H2} + \frac{E_\mathrm{H1}-E_\mathrm{H2}}{R_{s_1}+R_{s_2}} R_{s_2} \tag{8}$$

Equation (8) can be expressed as

$$E_\mathrm{H} = E_x B_z\left[\mu_2 + (\mu_1-\mu_2)\frac{n_1\mu_1}{n_2\mu_2+n_1\mu_1}\right] \tag{9}$$

The measured value of mobility evaluated from the Hall experiment μ_meas for AlGaN/GaN type HEMT heterostructures grown with the pressure modification of the MOVPE process is a combination of both mobilities and concentrations in each

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channel in accordance with Equation (9) and (2) and can be expressed as

$$\mu_{\text{meas}} = \mu_2 + (\mu_1 - \mu_2)\frac{n_1\mu_1}{n_2\mu_2 + n_1\mu_1} \tag{10}$$

In the case, when the second channel does not exist, i.e., $\mu_2 = 0$, the measured mobility is equal to 2DEG mobility $\mu_{\text{meas}} = \mu_1$. In the other case, when the mobility of 2DEG for some reason is equal to zero i.e., $\mu_1 = 0$, the measured mobility is equal to mobility in the second channel, $\mu_{\text{meas}} = \mu_2$. However, the case of $\mu_1 = 0$ does not exist in AlGaN/GaN type HEMT heterostructures grown with the pressure modification of the MOVPE process. To estimate the value of 2DEG mobility, μ_1, it is helpful to express Equation (9) in terms of sheet resistance in the second channel.

$$E_{\text{H}} = E_x B_z \left[\mu_2 + \frac{\mu_1 - \mu_2}{\frac{1}{q n_1 \mu_1 R_{s_2}} + 1}\right] \tag{11}$$

Therefore, the measured electron mobility of AlGaN/GaN type HEMT heterostructures, grown with the pressure modification of the MOVPE process, is

$$\mu_{\text{meas}} = \mu_2 + \frac{\mu_1 - \mu_2}{\frac{1}{q n_1 \mu_1 R_{s_2}} + 1} \tag{12}$$

and the 2DEG mobility

$$\mu_1 = \frac{1}{2}\left[\mu_{\text{meas}} + \sqrt{\mu_{\text{meas}}^2 + \frac{4(\mu_{\text{meas}} - \mu_2)}{q n_1 R_{s_2}}}\right] \tag{13}$$

2DEG mobility, μ_1, is therefore a function of four variables: sheet resistivity, R_{s_2}, and electron mobility, μ_2, of the second channel as well as the measured sheet carrier concentration, $n_s = n_1$, and measured electron mobility, μ_{meas}, evaluated from the Hall experiment. $\mu_1 = f(n_s, \mu_{\text{meas}}, \mu_2, R_{s_2})$.

4. Results and Discussion

The Hall measurement setup has been used to determine the sheet resistivity, electron mobility, and sheet carrier concentration of the samples #1, #2, #3, and #4 in the wide range of temperatures, from 77 to 420 K. The results are shown in **Figure 6**. The samples #3 and #4 with two conducting channels possess significantly lower electron mobility values for temperatures below 250 K. Above this temperature, the electron mobility starts to converge to the values obtained for samples with the single conducting channel, and above 400 K, every value is nearly indistinguishable. It is clear that 2DEG mobility dominates when the temperatures are below 250 K, when the acoustic phonon scattering is significantly smaller.[21] Therefore, the electrons in the second channel lower the values of 2DEG Hall mobility in samples with two conducing channels. This behavior is especially pronounced at low temperatures. **Figure 7** shows the measured sheet carrier concentration of the samples #1, #2, #3, and #4. The samples #3 and #4 possess higher values of concentration, which correspond to the presence of the second conducting channel. A slight variation of the measured sheet electron

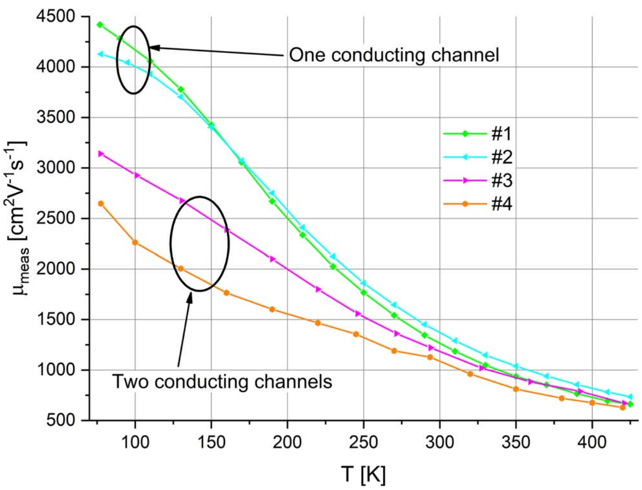

Figure 6. Measured electron mobility μ_{meas} in the function of temperature. The reference sample corresponds to the average values of #1 and #2 samples. Two conducting channels exist in the AlGaN/GaN type HEMT heterostructures #3 and #4 grown in the pressure-modified MOVPE process.

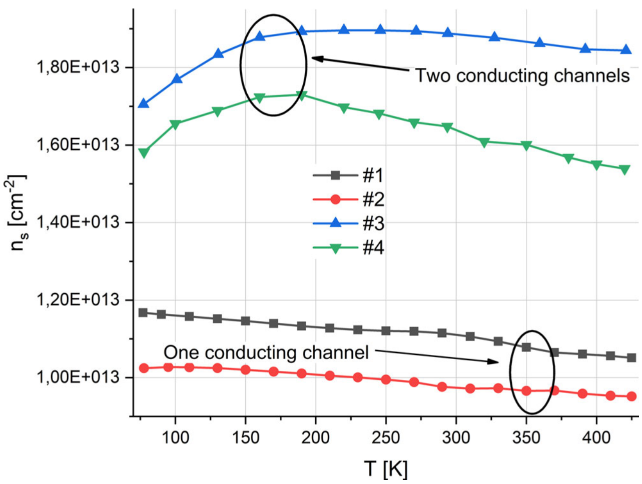

Figure 7. Sheet electron concentration as a function of temperature in the range of 77–420 K. The samples #3 and #4 possess higher values of concentration and the presence of the additional conducting channel is noticeable. The sheet electron concentration slightly changes with temperature.

concentration in the function of temperature probably results from the presence of the additional strain of the epitaxial layer with different thermal expansion coefficients.

Figure 8 and **9** shows the correction map for Hall measurements of AlGaN/GaN type HEMT heterostructures grown with pressure modification by the MOVPE process. In this case, the measured mobility corresponds to values of samples #3 and #4 at 77 K. $\mu_{\text{meas}} = 3141\,\text{cm}^2\,\text{V}^1\,\text{s}^{-1}$ and $\mu_{\text{meas}} = 2647\,\text{cm}^2\,\text{V}^1\,\text{s}^{-1}$, respectively, with sheet carrier concentration $n_s = 5 \times 10^{12}\,\text{cm}^{-2}$. The sheet resistivity, R_{s_2}, and electron mobility, μ_2, of the second conducting channel were at the range from 400 to 800 $\Omega\,\text{sq}^{-1}$ and from 300 to 600 $\text{cm}^2\,\text{V}^1\,\text{s}^{-1}$, respectively. The contour plot directly represents the values of 2DEG mobility μ_1 for the fixed second

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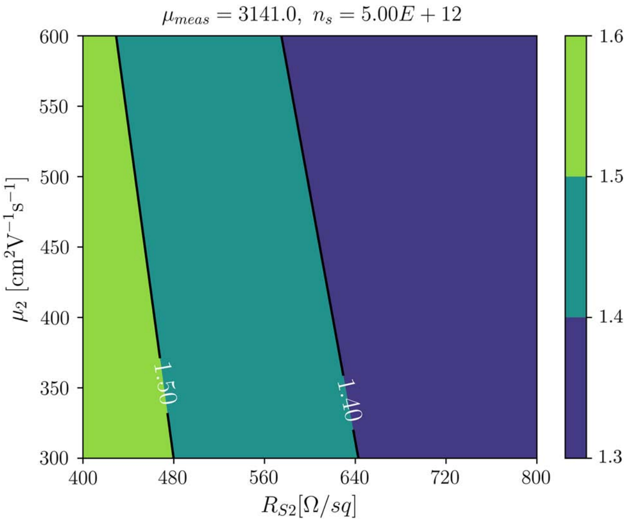

Figure 8. The correction map for Hall measurements on the AlGaN/GaN type HEMT heterostructures grown with pressure modification in the MOVPE process. The map was obtained for sample #3 at 77 K: $\mu_{meas} = 3141$ cm^2 V^{-1} s^{-1}, $n_s = 5 \times 10^{12}$ cm^{-2}, R_{s_2} from 400 to 800 Ω sq^{-1}, and μ_2 from 300 to 600 cm^2 V^1 s^{-1}. The correction coefficient varies these parameters from 1.3 to 1.6.

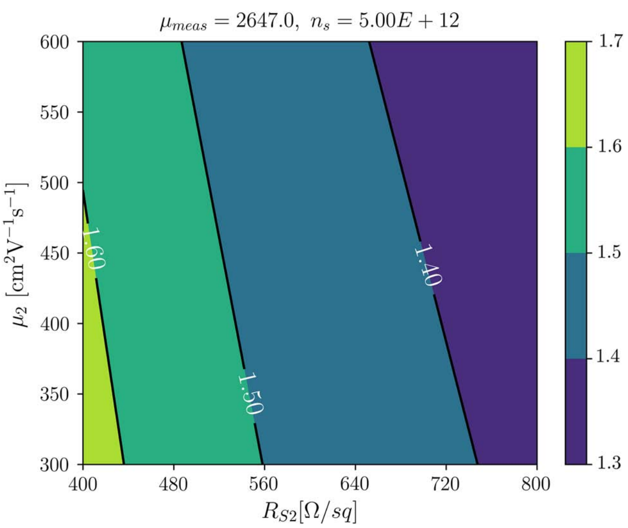

Figure 9. The correction map for Hall measurements on the AlGaN/GaN type HEMT heterostructures grown with pressure modification in the MOVPE process. The map was obtained for sample #4 at 77 K: $\mu_{meas} = 2647$ cm^2 V^{-1} s^{-1}, $n_s = 5 \times 10^{12}$ cm^{-2}, R_{s_2} from 400 to 800 Ω sq^{-1}, and μ_2 from 300 to 600 cm^2 V^1 s^{-1}. The correction coefficient varies these parameters from 1.3 to 1.7.

channel parameters obtained by multiplying the measured electron mobility μ_{meas} with the correction coefficient α using the quantity: $\mu_1 = \alpha\mu_{meas}$.

Figure 10 shows the correction map for measured mobility μ_{meas} equal to 1200 cm^2 V^1 s^{-1} and the sheet carrier concentration $n_s = 5 \times 10^{12}$ cm^{-2}. The sheet resistivity, R_{s_2}, and electron mobility, μ_2, of the second conducting channel were at the range from 4000 to 6000 Ω sq^{-1} and from 100 to 200 cm^2 V^1 s^{-1}, respectively.

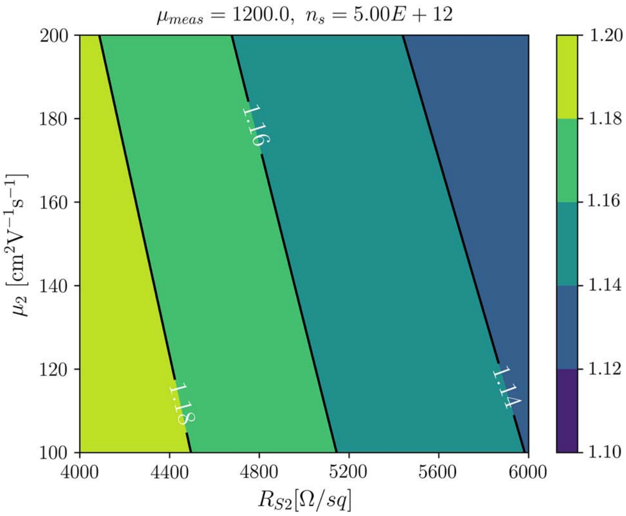

Figure 10. The correction map for Hall measurements on the AlGaN/GaN type HEMT heterostructures grown with pressure modification in the MOVPE process. The map was obtained for $\mu_{meas} = 1200$ cm^2 V^{-1} s^{-1}, $n_s = 5 \times 10^{12}$ cm^{-2}, R_{s_2} from 4000 to 6000 Ω sq^{-1}, and μ_2 from 100 to 200 cm^2 V^1 s^{-1}. The correction coefficient varies these parameters from 1.10 to 1.20.

5. Conclusions

The multilayer transport in AlGaN/GaN type HEMT heterostructures grown by the MOVPE process with the change in pressure during the growth of the GaN buffer to ensure its high resistivity was examined. The equivalent circuit of the heterostructure was developed that includes the presence of compensatory current in classical Hall measurements carried out at a wide range of temperatures from 77 to 420 K. The correction map was proposed (Figure 8–10) that enabled the estimation of the 2DEG mobility in the examined AlGaN/GaN type HEMT heterostructures. It was done by multiplying the measured value of mobility determined from Hall measurement by the correction coefficient α using the quantity $\mu_1 = \alpha\mu_{meas}$. It was assumed that the electrical parameters evaluated based on Hall measurements could be significantly different in the double-channel HEMTs[10] mainly due to the presence of the compensatory current.

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Conflict of Interest

The authors declare no conflict of interest.

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Keywords

2D electron gas mobilities, AlGaN/GaN, Hall effects, high electron mobility transistors, heterostructures

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[1] T. Mimura, *Fujitsu Sci. Tech. J.* **2018**, *54*, 3.
[2] B. S. Eller, J. Yang, R. J. Nemanich, *J. Vac. Sci. Technol., A* **2013**, *31*, 050807.
[3] J. P. Ibbetson, P. T. Fini, K. D. Ness, S. P. DenBaars, J. S. Speck, U. K. Mishra, *Appl. Phys. Lett.* **2000**, *77*, 250.
[4] R. Vetury, N. Zhang, S. Keller, U. K. Mishra, *IEEE Trans. Electron Devices* **2001**, *48*, 560.
[5] W. Wojas, J. Wojas, *Biul. Wojsk. Akad. Tech.* **2007**, *56*, 21.
[6] J. M. Tirado, J. L. Sánchez-Rojas, J. I. Izpura, *IEEE Trans. Electron Devices* **2007**, *54*, 417.
[7] M. J. Uren, K. J. Nash, R. S. Balmer, T. Martin, E. Morvan, N. Caillas, S. L. Delage, D. Ducatteau, B. Grimbert, J. C. De Jaeger, *IEEE Trans. Electron Devices* **2006**, *53*, 395.
[8] M. J. Uren, S. Karboyan, I. Chatterjee, A. Pooth, P. Moens, A. Banerjee, M. Kuball, *IEEE Trans. Electron Devices* **2017**, *64*, 2826.
[9] M. J. Uren, M. Cäsar, M. A. Gajda, M. Kuball, *Appl. Phys. Lett.* **2014**, *104*, 1.
[10] X. D. Wang, W. Da Hu, X. S. Chen, W. Lu, *IEEE Trans. Electron Devices*, **2012**, *59*, 1393.
[11] P. B. Klein, S. C. Binari, K. Ikossi, A. E. Wickenden, D. D. Koleske, R. L. Henry, *Appl. Phys. Lett.* **2001**, *79*, 3527.
[12] G. S. Leadstone, *Phys. Educ.* **1979**, *14*, 374.
[13] L. J. van der Pauw, *Phys. Tech. Rev.*, **1958**, *20*, 220.
[14] A. Kobus, J. Tuszyński, *Hallotrony i gaussotrony*, WNT, Warszawa, Poland **1966**.
[15] D. C. Look, *Electrical Caracterization of GaAs Materials and Devices*, John Wiley & Sons, New York **1989**.
[16] M. Glinkowski, B. Paszkiewicz, R. Paszkiewicz, *Proceedings of Advances in Electronic and Photonic Technologies* (Eds: D. Jandura, Ľ. Šušlik, P. Urbanová, J. Kováč), EDIS-Publishing Centre of UZ, Žilina, Slovakia **2019**, pp. 59–62.
[17] M. Wośko, B. Paszkiewicz, T. Szymański, R. Paszkiewicz, *Proceedings of 16th European Workshop on Metalorganic Vapour Phase Epitaxy*, Lund, Sweden **2015**, pp. 195–198.
[18] R. Larrabee, R. Thurber, *IEEE Electron Device Lett.* **1980**, *27*, 32.
[19] W. Marciniak, *Przyrządy półprzewodnikowe i Układy Scalone*, WNT, Warszawa, Poland **1979**.
[20] S. Kasap, P. Capper, *Springer Handbook of Electronic and Photonic Materials*, Springer International Publishing AG, Cham, Switzerland **2017**.
[21] J. H. Davies, *The Physics of Low-Dimensional Semiconductors*, Cambridge University Press, Cambridge **1998**.

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