Optica Applicata, Vol. XXXII, No. 3, 2002

Computer modelling of devices based on AlGaN/GaN heterostructure

Wojciech Kośnikowski, Tomasz Piasecki

The Faculty of Microsystem Electronics and Photonic, Wrocław University of Technology,
Wybrzeże Wyspiańskiego 27, 50–370 Wroclaw, Poland.

Computer simulation of AlGaN/GaN heterostructure heterostructure field effect transitior (HFET) and metal–semiconductor–metal (MSM) photodetector has been performed. The influence of AlGaN layer thickness and background electron concentration, as well as piezoelectric effect, on devices' parameters has been investigated. The results confirm the great importance of keeping low background electron concentration. The superiority of devices with AlGaN layer applied is shown. Thickness of AlGaN layer is not an important factor.

1. Introduction

Compounds of group III nitrides are promising semiconductor material for blue/UV emitters and detectors, solar-blind detectors and high temperature devices. However, mainly due to a lack of lattice-matched substrate, it is still hard to obtain good quality epitaxial A^{III}-N layers. It is important to learn how to manufacture good quality devices using materials we are able to achieve today.

Computer modelling of semiconductor devices is not only a way of reducing device's project cost, but also allows better understanding of device's physical mechanisms and easier optimisation of device's structure. However, one must remember that modelling is only an approximation of real structures and as such might not take into account all phenomena that have influence on device's final parameters. The goal of this work is to use computer simulation of HFET transistor and MSM ultraviolet photodetectors to optimise structures of these devices that are manufactured in our laboratory, and to check limitations of the package used in modelling the materials with highly defective crystalline structure. In this work we are using APSYS simulation software form Crosslight Software Inc. which allows 2D simulation of A^{III}-N based devices [1].

2. Structure of the devices

Both HFET transistor and MSM photodetector are based on single AlGaN/GaN heterostructure, as shown in Fig. 1. There is a thin AlGaN layer deposited on undoped, a few mm thick GaN buffer. In case of HFET transistor there are three contacts – two

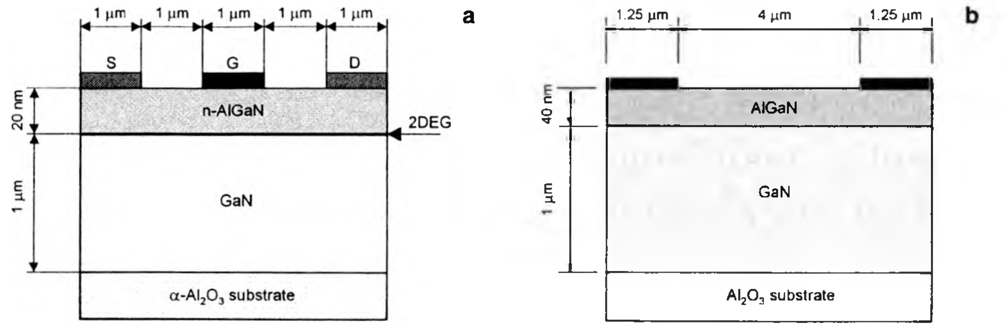

Fig. 1. Schematic cross-section of modelled devices: HFET (**a**), MSM (**b**).

ohmic for source and drain and one Schottky contact for gate; in case of MSM photodetector there are two Schottky contacts representing one period of MSM structure. In the work so far we have concentrated on analysing the influence of AlGaN layer thickness and electron concentration in GaN buffer on final devices characteristics, leaving structure dimensions fixed. Although GaN buffer is not intentionally doped, there is always a significant background electron concentration due to large number of crystalline structure defects. In case of HFET transistor, the piezoelectric effect in stressed AlGaN layer was also taken into consideration.

3. Simulation

Figure 2 shows a sample band and electron concentration diagram for HFET transistor, with 2-dimensional electron gas (2DEG) – the channel – created at GaN/AlGaN interface. Doping concentration in AlGaN layer has been chosen so that the depletion region caused by a gate contact reaches the channel, and any negative potential applied to the gate decreases the channel width.

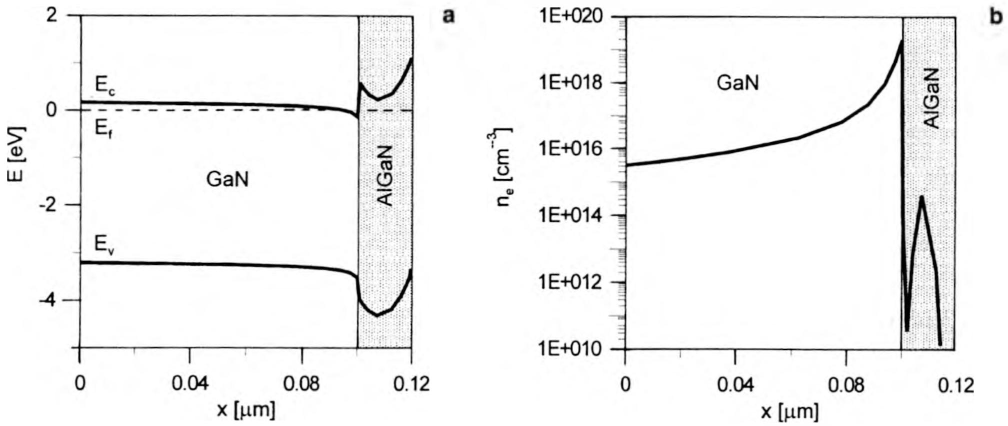

Fig. 2. Band diagram (**a**) and electron concentration (**b**) at the heterostructure (HFET, equilibrium).

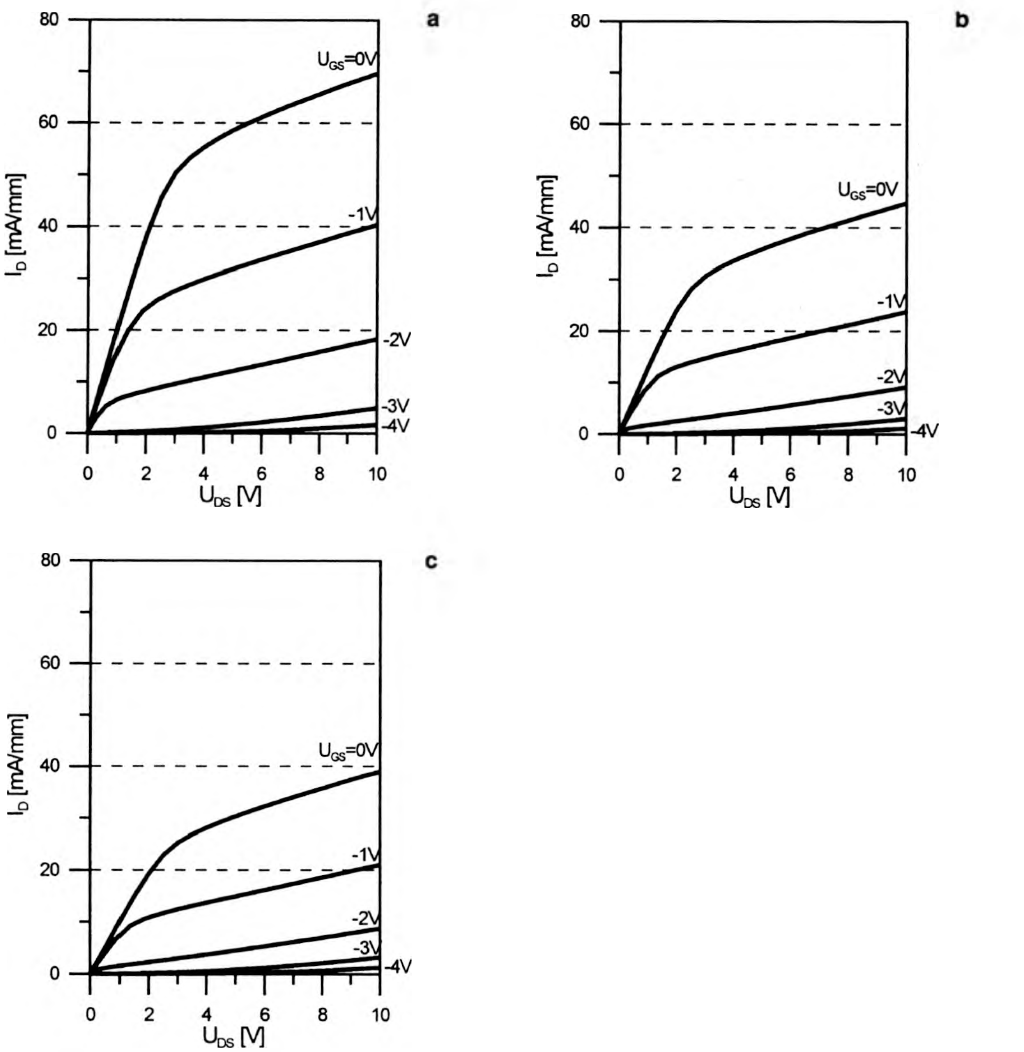

Fig. 3. HFET output characteristics depending on AlGaN layer thickness: 20 nm (**a**), 35 nm (**b**), 50 nm (**c**).

A series of simulations has been performed to check AlGaN layer thickness and electron concentration in GaN buffer on transistor's output characteristics. Their results are presented in Fig. 3 and Fig. 4, calculated parameters are presented in Table 1. When increasing AlGaN layer thickness both transconductance g_m and open-channel current I_{DSO} decreases, these effects are caused by smaller gate influence on the channel and bigger source-channel and drain-channel resistances. However, with AlGaN layer thickness between 20 and 50 nm these changes are not very big. Electron concentration in GaN buffer is found to be much more important factor. Although the output characteristics is quite similar for electron concentration 10^{14} cm^{-3} and 2×10^{5} cm^{-3}, at electron concentration of 10^{17} cm^{-3} transistor does not

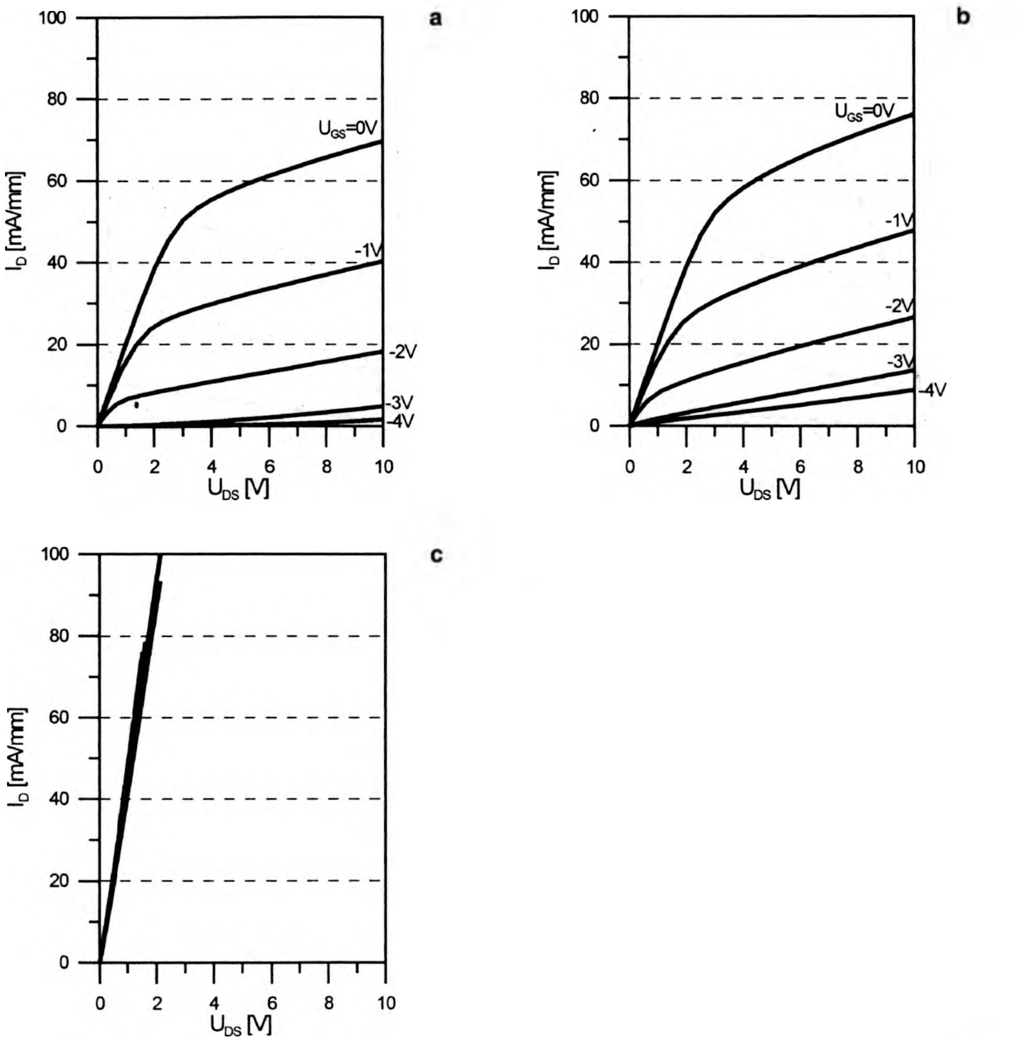

Fig. 4. HFET output characteristics depending on electron concentration in GaN buffer: 1×10^{14} cm^{-3} (**a**), 2×10^{15} cm^{-3} (**b**), 1×10^{17} cm^{-3} (**c**).

T a b l e 1. Calculated HFET parameters for different configurations.

		d_{AlGaN}		
		20 [nm]	35 [nm]	50 [nm]
$n_e = 1\times10^{14}$ [cm^{-3}]	g_m [mS/mm]	29.3	21.0	17.9
	g_{ds} [mS/mm]	2.21	1.79	1.73
	I_{DSO} [mA/mm]	69.7	44.8	39.0
$n_e = 2\times10^{15}$ [cm^{-3}]	g_m [mS/mm]	28.2	20.4	17.6
	g_{ds} [mS/mm]	2.77	2.39	2.37
	I_{DSO} [mA/mm]	76.0	52.5	47.2

function properly. Further investigation shows that with this electron concentration source-drain current is no longer limited to 2DEG channel but flows through GaN buffer, thus the structure behaves like plain resistor.

Frequency analysis showed f_T value in the range of 2.8–3.8 GHz, depending on AlGaN layer thickness.

The influence of piezoelectric effect was also investigated. The electric field caused by this phenomenon in stressed AlGaN layer increases the electron concentration in 2DEG [2]. The simulation software we are using does not have models for this effect. We have overcome this limitation by putting fixed charges on both sides of AlGaN layer, charges surface concentration has been taken according to BYKHOVSKI *et al.* [3]. The difference between output characteristics without and with piezoelectric effect is shown in Fig. 5 – it is clear that piezoelectric effect improves AlGaN/GaN HFET performance as it increases 2DEG sheet concentration, in this case from 3×10^{12} cm^{-2} to 5×10^{13} cm^{-2}.

Similar test have been applied to MSM photodetector model and their results are shown in Figs. 6, 7 and Tab. 2. The power of incident light was set to 1 kW/m^2, wavelength $\lambda = 350$ nm, DC voltage applied to the contacts (unless otherwise noted) was 3 V.

It is clear that the presence of AlGaN layer greatly improves detector properties by lowering the dark current (top layer of a wide-bandgap material acts as a passivation layer and decreases the surface current). Again, the thickness of this layer is not critical, in the range of 10–40 nm the detector parameters are similar. In contrary, electron concentration in the structure greatly influences both dark current and detector sensitivity. Under previously assumed conditions, electron concentration in undoped GaN buffer establishes at level 1×10^{12} cm^{-3}.

From the results obtained we can conclude that initial electron concentration of order 1×10^{13} cm^{-3} and above would decrease detector sensitivity. Higher electron

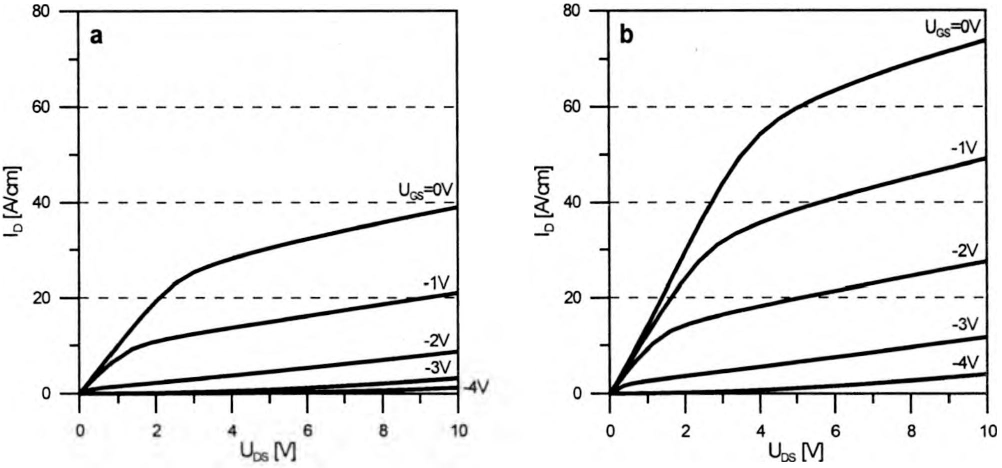

Fig. 5. HFET output characteristic without (a) and with (b) piezoelectric effect.

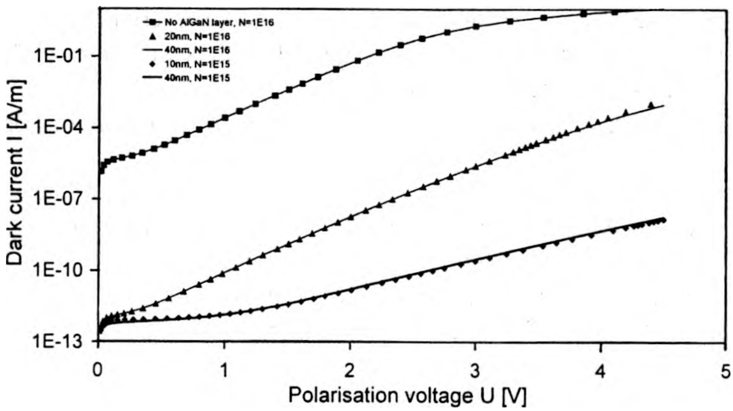

Fig. 6. Influence of AlGaN layer thickness and background electron concentration N [cm^{-3}] on photodetector dark current.

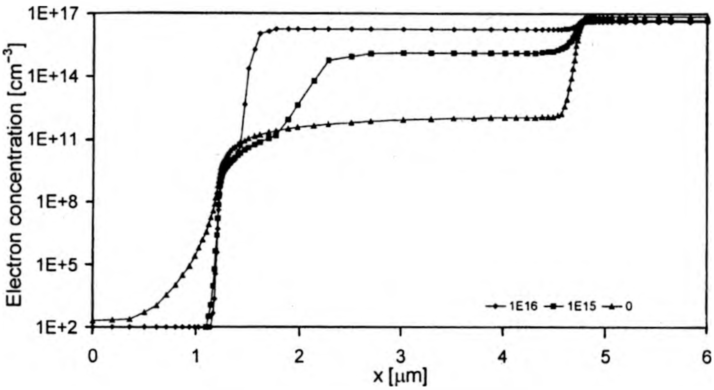

Fig. 7. Electron concentration under the AlGaN layer (1 kW/m^2 incident light), depending on background electron concentration in GaN buffer (U = 3 V).

T a b l e 2. Calculated photodetector parameters.

n_e [cm^{-3}]	d_{AlGaN} [nm]	Polarisation [V]	Dark current	Sensitivity [A/W]
10^{16}	40	1.5	2.07 [pA]	0.015
		3.0	3.87 [nA]	0.020
	20	1.5	2.04 [pA]	0.016
		3.0	3.95 [nA]	0.022
10^{15}	40	1.5	6.53 [fA]	0.031
		3.0	0.47 [pA]	0.046
	10	1.5	6.12 [fA]	0.034
		3.0	0.40 [pA]	0.050
—	40	1.5	0.64 [fA]	0.127
		3.0	0.84 [fA]	0.139

concentration causes decreasing in reverse-polarised contact depletion region thickness (Fig. 7), decreasing detector active region volume. Electron concentration of 1×10^{15} cm^{-3} would not affect sensitivity if the distance between electrodes was 1 μm or less.

Frequency characteristics have been calculated from step response using Fourier transformation and the f_{3dB} value obtained were approximately 1 GHz. AlGaN layer thickness and electron concentration did not show major influence on this value, neither did the decreasing absorption region thickness (to 0.5 μm), achieved by inserting another AlGaN layer below GaN buffer.

4. Conclusions

A series of simulations concerning AlGaN/GaN devices such as HFET transistor and MSM photodetector has been performed and some of their results presented. In both devices the top AlGaN layer greatly improves their parameters, with the exact layer thickness not being an important factor. In contrary, electron concentration in GaN buffer has turned out to be critical for proper device functioning. For HFET is should be kept at the level lower than about 1×10^{16} cm^{-3}, while for 1 μm MSM photodetector the threshold value is 1×10^{15} cm^{-3}. Piezoelectric effect in AlGaN layer has positive influence on transistor parameters.

References

[1] *APSYS User's Manual*, Crosslight Software Inc., 2000.
[2] PEARTON S.J., REN F., ZHANG A.P., LEE K.P., Mater. Sci. Eng. **R30** (2000), 55.
[3] BYKHOVSKI A., GELMONT B., SHUR M., J. Appl. Phys. **74** (1993), 6734.

Received May 13, 2002