Influence of Ionization Modelling for Mg-doped GaN on Transfer and Breakdown Characteristics of Vertical GaN-MOSFET

Martin Weigel[1*], Roland Stenzel[1], Wilfried Klix[1], Rico Hentschel[2], Andre Wachowiak[2], Thomas Mikolajick[2,3]

[1] University of Applied Sciences, Dresden, Germany, *martin.weigel@htw-dresden.de
[2] NaMLab gGmbH, Dresden, Germany
[3] Institute of Semiconductors and Microsystems, University of Technology, Dresden, Germany

Abstract

The p-doping of GaN is typically done with Mg. Because of its high ionization energy Mg is not completely ionized at room temperature. This has to be considered in simulations for defining characteristic values and designing devices, if p-GaN with Mg incorporation is involved. In this work the influence of simulation with a constant ionization rate in comparison to a model dependent non-uniform ionization rate on device characteristics of a vertical GaN-MOSFET is investigated. Furthermore the different simulation variants were verified by using literature data.

Introduction

Devices based on wide bandgap semiconductor GaN have a high application potential for power electronics, because of high breakdown field strength and low switching losses [1,2]. The vertical structure enables an area efficient device design for a high breakdown voltage because long drift distances can be integrated in vertical direction. Furthermore, the MOSFET is usually a normally-off device, which is required in numerous applications. The threshold voltage can be tuned in the positive voltage region in dependence of the gate dielectric layer and p-doping of the channel layer.

For dimensioning the device, simulation is indispensable to define the characteristic values. In this process the accurate modelling of ionization of p-doped GaN:Mg is an important aspect. Because of the high ionization energy of about 0.2 eV, Mg-acceptors are not fully ionized by thermal activation at 300 K. This work shows the influence of different variants of ionization modelling on the transfer and breakdown characteristics of the vertical GaN-MOSFET shown in Figure1.
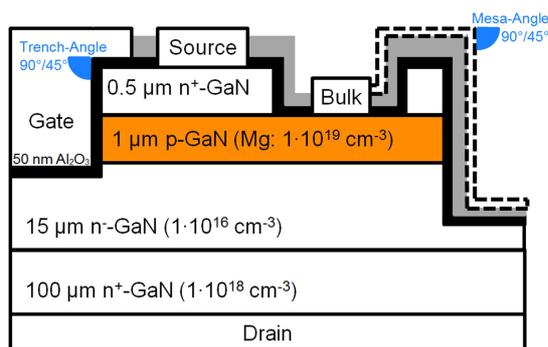

Figure 1. Vertical GaN-MOSFET structure used in this work [3]

Simulation Models

The ionization of acceptors in p-doped semiconductors can be calculated by the Fermi-Dirac distribution [4]:

$$N_A^- = \frac{N_A}{1 + g_A \cdot \exp\left(\frac{W_A - W_F}{k_B \cdot T}\right)}$$

The ionization energy [4] and fermi level [5] are defined by:

$$\Delta E_A = W_A - W_V \qquad W_F - W_V = k_B \cdot T \cdot \ln\left(\frac{N_V}{N_A^-}\right)$$

By combining these formulas the ionized acceptor density can be calculated:

$$N_A^- = \frac{\sqrt{N_V^2 + 4 \cdot N_V \cdot N_A \cdot g_A \cdot \exp\left(\frac{\Delta E_A}{k_B \cdot T}\right)} - N_V}{2 \cdot g_A \cdot \exp\left(\frac{\Delta E_A}{k_B \cdot T}\right)}$$

An effective density-of-states of one valence band of $N_V = 3.3 \cdot 10^{19}$ cm^{-3} was used, here. Furthermore the ionization energy depends on total doping concentration [4]:

$$\Delta E_A = \Delta E_{A,0} - \alpha_A \cdot N_{tot}^{1/3}$$

The parameters for these calculations have been taken from literature and are shown in Figure 2 [6-10]. It is assumed that the Mg concentration is equal to N_A and N_{tot}. For the degeneracy factor g_A different values are reported in different publications. Most of them specify $g_A = 2$ [11] but also $g_A = 4$ is mentioned [12]. Looking at the band diagram of GaN there is a triple splitting of the valence band [13], so that $g_A = 6$ is also a possible value. For comparative simulations $g_A = 2$ and $g_A = 6$ have been chosen.

In the following investigations the influence of different simulation variants will be presented. Therefore transfer and breakdown characteristics of the structure shown in Figure 1 were investigated. A constant ionization rate for the total p-region calculated with the formula above in comparison to the model dependent non-uniform ionization rate for p-GaN was used in simulations.

The outcomes are four different simulation scenarios:

(I) Constant ionization rate of 4.77 % ($g_A = 2$)
(II) Constant ionization rate of 2.78 % ($g_A = 6$)
(III) Model dependent non-uniform ionization rate ($g_A = 2$)
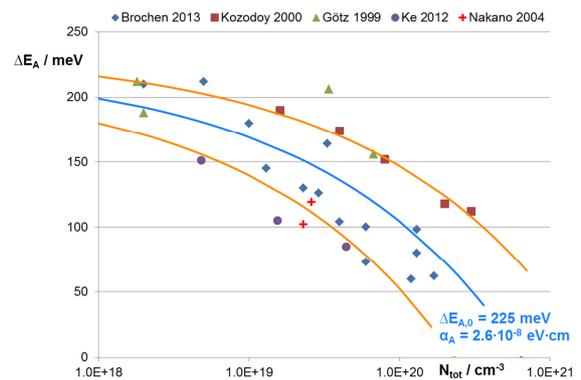(IV) Model dependent non-uniform ionization rate ($g_A = 6$)

Figure 2. Literature data for the doping dependent ionization energy for Mg in GaN [6-10]

Results and Discussion

The results for the simulation of transfer characteristics with the four described variants are shown in Figure 3. Different threshold voltages result from the simulation variant. The reason of that is the different ionization rate of p-GaN at the MOS interface. For the constant ionization rates (I) and (II) there is only a small difference in threshold voltage caused by the slight difference in constant ionization rates.
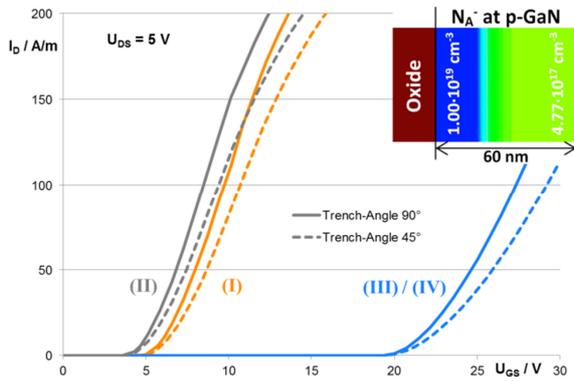
Figure 3. Transfer characteristics of the different simulation variants described in the text (Inset: ionized doping for (III) at U_{GS} = 20 V)

By using model dependent ionization rate the bending of valence band at MOS interfaces is considered. Because of this the difference between acceptor and quasi fermi level decreases and the ionization rate increases up to 100 % at the interface (see inset of Figure 3). Therefore the threshold voltage is much higher. There is also a difference in the slope of the curves based on trench-angle for each pair, which is mainly caused by the increase in channel length for 45° trench-angle. (For a given gate-source voltage, the longer channel has a higher channel resistance and causes an overall decrease of drain current.)

The simulation results of the breakdown voltage are shown in Table 1. The breakdown mechanism is impact ionization. The results show some differences. For example the structure without field plate and 45° mesa-angle should be discussed. Figure 4 shows ionized doping concentration and electric field at the p-n junction at mesa etch for a constant (I) and a model dependent ionization rate (III). Here the reason of different breakdown voltages of these variants is visible. By using a model dependent ionization rate the deflection of valence band at the p-n junction and the semiconductor-oxide interface leads to a high concentration of ionized acceptors resulting in a higher electric field. Because of this the breakdown starts at a lower voltage. The differences between (I) and (II) can be explained by the relative small differences in ionization rates resulting in different ionized acceptor densities. For (III) and (IV) there is no difference because in both cases the ionized acceptor density at the p-n junction is close to 100 %.

Scenario		(I)	(II)	(III)	(IV)
without field plate	90° mesa-angle	1700 V	1800 V	1900 V	1900 V
	45° mesa-angle	1300 V	1600 V	700 V	700 V
with field plate	90° mesa-angle	1500 V	1800 V	1300 V	1300 V
	45° mesa-angle	1700 V	1800 V	1600 V	1600 V

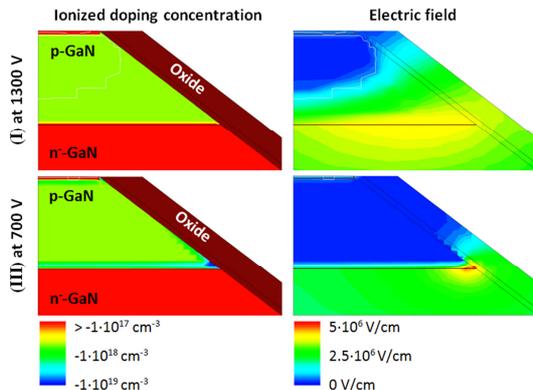**Table 1.** Breakdown voltages for the scenarios with 90° trench-angle

Figure 4. Comparison of ionized doping concentration and electric field at breakdown voltage for variants (I) and (III) in structures without field plate and 45° mesa-angle

After presenting the results of different simulation variants it has to be verified which of these models should be used for future simulations. Therefore, the threshold voltage of lateral MOSFET devices from literature [14-18] were compared with simulation results of test structures based on these publications for the different variants (I) and (III). The results are shown in Figure 5. Considering the inaccuracy in consequence of simplifications for simulation and missing detailed information of micro-processing in literature, the model dependent non-uniform ionization rate provides more realistic simulation results, although some variability is obvious.
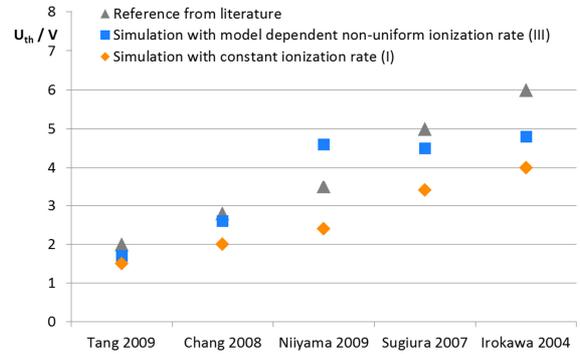

Figure 5. Comparison of threshold voltage from simulations with constant ionization rate (I) and model dependent non-uniform ionization rate (III) to literature values [14-18]

Conclusions

The presented results show that modelling of ionization in p-GaN plays an important role in simulations for device performance and design aspects. Different models have large impact on final simulation results. The comparison with literature shows that the use of model dependent non-uniform ionization rate provides better results. Also the full ionization at the p-n junction and the MOS interface has to be considered in the calculation of the space charge region.

References

[1]   Ueda, D., IEEE IRPS, 3C.2.1, 2013
[2]   Chowdhury, S. et al., Semicond. Sci. Tech. 28, 074014, 2013
[3]   Weigel, M. et al., Proceedings WOCSDICE 39, 45, 2015
[4]   Synopsys Inc., Sentaurus Device User Guide Version J-2014.09, Montain View, 2014
[5]   Goßner, S., "Grundlagen der Elektronik", p. 18, Shaker Verlag, Aachen, 2008
[6]   Brochen, S. et al., Appl. Phys. Lett. 103, 032102, 2013
[7]   Kozodoy, P. et al., J. Appl. Phys. 87, 1832, 2000
[8]   Götz, W. et al., Mater. Sci. Eng. B59, 211, 1999
[9]   Ke, W.-C. et al., Mater. Chem. Phys. 133, 1029, 2012
[10]   Nakano, Y. et al., J. Appl. Phys. 96, 415, 2004
[11]   Pankove, J. I., Moustakas, T. D., "Gallium Nitride (GaN) II", p. 188, Academic Press, San Diego, 1999
[12]   Lieten, R. R. et al., J. Phys. D: Appl. Phys. 44, 135406, 2011
[13]   Vurgaftman, I. et al., J. Appl. Phys. 89, 5815, 2001
[14]   Tang, K. et al., J. Electron. Mater. 38, 523, 2009
[15]   Chang, Y. C. et al., Appl. Phys. Lett. 93, 053504, 2008
[16]   Niiyama, Y. et al., Furukawa Review 36, 1, 2009
[17]   Sugiura, S. et al., Electron. Lett. 43, 952, 2007
[18]   Irokawa, Y. et al., Appl. Phys. Lett. 84, 2919, 2004

Acknowledgment