Influence of doping profile of GaN:Fe buffer layer on the properties of AlGaN/AlN/GaN heterostructures for high-electron mobility transistors

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Abstract. The effect of the Fe doping profile of the GaN buffer layer in the heterostructures for high-electron mobility transistors was studied experimentally and by computer simulation. The exponential Fe tail extending to the nominally undoped layers may greatly affect the properties of the structure. Reducing the distance between the channel and the Fe-doped buffer to less than 1 μm results in a decrease in the density and mobility of the two-dimensional electron gas. It also leads to the higher off-state avalanche breakdown voltage and reduced leakage current. A good agreement between simulation and experimental data is obtained when taking into account a Fe segregation effect, while an abrupt doping profile lead to significant discrepancies between them.

1. Introduction

Heterostructures based on InGaAlN material system are promising for next-generation power and high frequency electronics due to their unique properties: wide range of bandgap energies (from ~0.7 eV for InN to ~6.2 eV for AlN), high electron saturation velocity and high breakdown voltage. The polar nature of III-N materials enables to fabricate high-electron-mobility-transistors (HEMTs) with a two-dimensional electron gas (2DEG) density of $1\text{ - }3\times10^{13}$ cm$^{-2}$ and mobility up to 2200 cm$^2$V$^{-1}$s$^{-1}$ at room temperature [1] even without intentional doping. In order to ensure proper drain-source current saturation, complete channel pinch-off and low loss at high frequencies, an insulating buffer layer beneath the channel is required [2]. However, nominally undoped GaN layers are usually n-type with a rather high carrier density of $10^{16}$-$10^{17}$ cm$^{-3}$ due to background impurities and crystal imperfections. Moreover, a high-purity intrinsic semiconductor (even the wide bandgap one) with no significant density of thermally generated mobile carriers can effectively conduct an electric current if charge carriers are injected into it from an external source and an electric field is applied [3]. In the case of GaN-based HEMTs, the subcontact regions, the channel region and even the substrate may serve as a source of electrons [4].

There are two main approach to obtain insulation GaN buffer layers for HEMTs. One of them is to tune the growth conditions in such way as to intentionally increase the density of the threading edge dislocations that form deep acceptor levels [5]. However, this unavoidably results in the degradation of other electrophysical properties of the devices. In particular, dislocation lines may serve as vertical
leakage paths [6], and the scattering by dislocations with density of $10^9$-$10^{10}$ cm$^{-2}$ may significantly reduce the 2DEG mobility, especially at low temperatures and/or when the 2DEG density is low [7]. Moreover, the correlation between the origin of the insulating character of the layers and the growth conditions is not very clear and may be strongly dependent on the growth system [8], and thus reproducibility issues exist [9]. The absence of extra reactor contamination may be noted as a slight advantage of the method.

The second approach is to intentionally dope the buffer layers with deep acceptor impurities. Carbon is one of those ones, which may be provided by the separate carbon-containing precursor such as different hydrocarbons (by MOCVD-metal organic chemical vapor deposition [10], halide vapor phase epitaxy/HVPE [11] and MBE-molecular beam epitaxy [12]), carbon halides (by MOCVD [13] and MBE [14, 15]) or even graphite (by MBE [16, 17]). Contrary to Fe and Mg, carbon shows no segregation or memory effect, and a doping profile can be controlled precisely. Without the need of strong intentional deviation from the optimal growth conditions, high-resistivity GaN layers with a relatively high crystal quality can be growth. But there are several drawbacks. First, carbon in GaN has an amphoteric nature [18, 19], acting either as an acceptor or donor. Although most papers report insulating character of C-doped GaN, both n-type [17, 20] and p-type [13, 21] layers were observed, which apparently indicates the dependency on the growth condition. Moreover, carbon can induce a strong current collapse [22] and increased dynamic $R_{ON}$ at high temperatures [23]. As for the growth, introduction of carbon in the initial stage of the growth on sapphire substrate hinders the coalescence of initial nuclei, impairs the crystal perfection and raises the parasitic conductivity [24]. The formation of pinholes is observed for GaN:C layer with carbon concentration of $1-2 \times 10^{18}$ cm$^{-3}$ and higher [25, 26], that may lead to the electric breakdown at relatively low voltages. In the case of MOCVD, carbon may be provided by the same precursor gas as for Ga atoms (e.g. trimethylgallium [27]) under special growth conditions applied. However, an increasing density of threading edge dislocations was observed for the layers with increased carbon concentration [28], leading to a lower electron mobility.

The alternative is to use iron instead of carbon as a dopant, which is suitable for any substrate material. In contrast to carbon, the Fe incorporation is easier to control as it shows linear dependence on the precursor partial pressure and is insensitive to growth temperature and reactor pressure [29, 30]. Fe in GaN acts as a deep acceptor only that pins the Fermi level slightly above the half of the bandgap [31], and the insulating character of Fe-doped GaN is ensured regardless the growth conditions. It was also shown that high Fe doping during GaN layers deposition on SiC can promote efficient dislocation filtration [32]. The main disadvantage is incorporation of Fe atoms into subsequently growing layers after turning off the flow of the Fe precursor due to diffusion/segregation [29]. As a result, the doping profile is not abrupt, and a Fe exponential ‘tail’ if formed in nominally undoped layers, which may extend to the channel region [29, 33, 34] and deteriorate the device characteristics. In contrast to the Mg memory effect, which is mostly due to the reactor contamination and which can be efficiently suppressed by in-situ etching [35] or low-temperature pulsed growth [36], a Fe tail is related to the Fe-doped sample itself. In order to reduce Fe concentration in nominally undoped layers, an ex-situ acid treatment between the growth of the GaN:Fe and the subsequent layers [29] can be applied, but only a slight reduction of Fe was achieved. Another method is to use so-called strain-engineered layers [33, 34]. Unfortunately, we did not succeed to reproduce the results. One more disadvantage of iron-doping is that a deterioration of the morphology of heavily-doped GaN:Fe is often observed [26,37]. However, an efficient insulating character is usually achieved at lower iron concentration.

There are a lot of impurities that can be used to obtained semi-insulating GaN buffer layers, such as Mn [38], Cr [39], Zn [40], Be [41, 42], Mg [43, 44] and others. Except for Mg, they all show no segregation or memory effect, but the characteristics achieved are usually worse compared to more conventional techniques. It is worth mentioning a novel approach based on the carbon/iron co-doping [26]. According to the preliminary studies, it allows to achieve high-resistivity GaN epilayers with a surface morphology better than those of GaN:C and GaN:Fe. However, this approach is its infancy and the process of searching for the optimal growth conditions is complicated by the presence of an additional precursor in a reactor (i.e. additional parameters including e.g. C and Fe concentrations and
their ratio, partial pressure and flow rate of carbon and iron precursor gases, etc.), extensive further investigations are needed. Therefore, we consider Fe-doped buffer layers to be preferable from a short-term perspective.

In this work, the influence of the distance between the channel and the Fe-doped buffer and the Fe segregation on the properties of AlGaN/AlN/GaN heterostructures with 2DEG for HEMTs was investigated via computer simulation and experimentally.

![Figure 1. Epitaxial layer schematic.](image)

**Figure 2.** (a) Fe distributions with and without exponential tail used in simulations. Shaded areas show concentration of ionized Fe atoms at equilibrium. Symbols are experimental SIMS depth profile of Fe. (b) Calculated conduction band energy with and without an Fe exponential tail and without Fe doping.

### 2. Simulation and experimental details

The Silvaco ATLAS drift-diffusion solver was used for simulations. Our standard HEMT structure with 24 nm Al$_{0.24}$Ga$_{0.86}$N barrier, ~0.75 nm AlN interlayer and GaN channel and buffer layers was investigated. The total thickness of the GaN layers was 4 μm. The schematic of the HEMT structure is shown in figure 1. Fe-induced traps in buffer layer was simulated as acceptor-like traps with an energy levels 0.7 eV below the conduction band and a capture cross section of 10$^{-13}$ cm$^2$ [45]. The simulations were conducted with and without considering a Fe exponential tail. No other trap levels were considered. The gate was considered a Ni Schottky contact with a work function of 5.16 eV. Since the buffer layers are thick enough, the substrate/buffer interface was modeled as a zero Neumann boundary condition. The Farahmand Modified Caughey-Thomas model [46] (FMCT.N flag in the MOBILITY statement) was used to simulate the dependence of the low-field mobility on the doping concentration. The high-field mobility was modeled by the Farahmand model [45] with the parameter set corresponding to Chen et al. [47] (CHEN.N flag in the MOBILITY statement). For breakdown simulations, the Selberherr impact ionization model [48] (SELF flag in the IMPACT statement) was used. The default ATLAS database values were used for the other material parameters.

The set of several samples was grown by MOCVD on c-face (0001) sapphire substrate in our in-house Dragon-125 epitaxial system with a horizontal reactor. Trimethylgallium, trimethylaluminum, ammonia and ferrocene as a source of Fe atoms were used as precursors. The intentional doping of the AlGaN and AlN barrier layers was not used. The samples differ from one another in the thickness of the nominally undoped GaN layer grown after turning off the ferrocene flow (in other words, the distance between the GaN:Fe buffer and the 2DEG interface). The mobility and 2DEG density were estimated by the Hall measurements using the van der Pauw method. Some samples were additionally...
analyzed by means of capacitance-voltage (CV) profiling and secondary ion mass spectrometry (SIMS).

3. Results and discussion
First, SIMS analysis of several samples was carried out to estimate the distribution of Fe atoms. The obtained SIMS depth profiles have a plateau in the buffer layer region with the Fe concentration of \( \sim 10^{18} \text{cm}^{-3} \) which exponentially decreases by a factor of 10 every \( \sim 0.4 \mu \text{m} \) after turning off the ferrocene source (figure 2a). This is in good agreement with the references. Then, the one-dimensional simulation with and without a Fe exponential tail was carried out. As one can see from figure 2b, the conduction band energy near the 2DEG interface of the structure with an abrupt doping profile (without the segregation effect) is more like the one of the undoped structure, so for that, the calculated 2DEG density (figure 3) is almost independent of the distance to the GaN:Fe buffer layer. In contrast, introduction of the Fe tail into the simulation model results in significant modification of the conduction band profile. It was found that Fe impurities in the region near the 2DEG interface were almost completely ionized (blue shaded area in figure 2a), so the electric field screening could be assumed as an origin of the difference between the conduction bands alignment. The calculated 2DEG density vs. the distance to the buffer layer agrees well with the measured values of the 2DEG Hall density (symbols in figure 3) when the Fe exponential tail is taken into account. The decreasing of the 2DEG density with the reduced distance to the Fe-doped layer was additionally confirmed by CV profiling (the inset in figure 3).

Figure 3. The calculated 2DEG density versus the distance between the 2DEG interface and Fe-doped buffer layer with and without Fe exponential tail. Symbols are the measured data averaged over various points on the wafer/samples, error bars indicate standard deviation. The inset shows CV concentration profiles of the samples with 1.5 and 0.5 \( \mu \text{m} \) distance to the GaN:Fe buffer.

Figure 4. The measured 2DEG mobility versus the distance between the 2DEG interface and Fe-doped buffer layer with and without Fe exponential tail. Symbols are data averaged over various points on the wafer and different samples with the same design; error bars indicate standard deviation. Dashed line is a guide for the eye. The value for the structure with unintentionally doped highly-dislocated buffer layer is given for comparison.

The measured 2DEG mobility versus the distance to the GaN:Fe buffer layer is shown in figure 4. As one can see, reducing the distance to less than 0.9 \( \mu \text{m} \) leads to 10-20% mobility degradation. According to the SIMS data, the concentration of iron atoms in the channel region may be of the order of \( \sim 10^{17} \text{cm}^{-3} \) and higher. Moreover, as stated above, the impurity near the 2DEG interface are completely ionized. Therefore, ionized impurity scattering is apparently responsible for the mobility degradation. The hypothesis of deterioration of the AlN/GaN interface and increased interface-
roughness scattering rate cannot, however, be dismissed. A detailed analysis of the scattering rate is planned and will be published elsewhere. Nevertheless, in contrast to threading dislocations that usually pierce through the whole structure from the buffer to the 2DEG, the presence of the ionized Fe scattering centers can be controlled by choosing the optimal concentration profile. Therefore, the use of less dislocated Fe buffer enables to decrease the dislocation scattering rate with no significant increase in the ionized impurity scattering, and the total mobility of the 2DEG is expected to be higher.

The leakage current and off-state breakdown voltage are other important parameters of HEMTs. In order to estimate the influence of a Fe-doped buffer, two-dimensional simulations of a ‘toy’ structure were carried out. The simulations without the impact ionization model were conducted to ensure the avalanche character of the sharp increase of the current. The obtained current-voltage characteristics at the gate voltage of -20 V of the structures with and without considering the iron segregation effect are shown in figure 5. As one can see, the structures with an abrupt doping profile (figure 5b) have much higher buffer leakage currents, which are determined by buffer trapping. Moreover, the avalanche breakdown in that case occurs at the same drain voltages for all the distances except 0.5 μm, which do not match the experimental observations. Taking into consideration a Fe exponential tail completely change the situation: the leakage currents are significantly reduced due to the presence of the traps closer to the channel in the buffer layer and the dependence of the breakdown voltage on the distance to the Fe-doped buffer becomes much more prominent. This is in good qualitative and order-of-magnitude agreement with experimentally observed breakdown voltages values obtained during interdevice insulation tests.

![Figure 5](image_url)

**Figure 5.** The current-voltage characteristics of the structures with different distance between Fe-doped buffer and 2DEG interface with (a) and without (b) Fe exponential tail. The dashed lines are results without the impact ionization model. The red horizontal line indicates the “standard” breakdown current of 1 mA/mm and is a guide for the eye.

It may be confusing that in the case of the structure with no tail of the Fe the leakage is higher and the breakdown occurs at lower drain voltage (i.e. lower electric field). But according to the Selberherr model, the electron impact ionization generation rate is:

$$G_n = \alpha_n \frac{|J_n|}{q}$$

and the ionization coefficient $\alpha_n$ is given by:

$$\alpha_n = A_n \exp\left(-\frac{B_n}{|E|}\right)^{\beta_n}$$
where $E$ is the electric field, $J_n$ is the current density, $A_n$, $B_n$ and $\beta_n$ are the model parameters. It is clearly seen, that not only the high electric field, but also the high current can initiate the avalanche breakdown. Thus, the obtained results seem to be reasonable. Furthermore, an important implication is worth to be emphasized: in order to fabricate the device with a high avalanche breakdown voltage, one should optimize both the electric field distribution (via gate [49, 50, 51], drain [51] and/or source [50, 51] field-plate engineering, optimization of passivation dielectric [52]) and the value of leakage currents (e.g. via iron/carbon co-doping or composite GaN:Fe/GaN:C buffer).

4. Conclusion
The influence of the doping profile of the GaN:Fe buffer layer on the electrophysical properties of AlGaN/AlN/GaN heterostructures for high-electron mobility transistors was investigated experimentally and by computer simulation. It was found that the reducing the distance from the 2DEG to the Fe-doped buffer layers resulted in significant improvement of the avalanche breakdown and leakage current characteristics. On the other hand, the Fe doping tail exponentially extending into nominally undoped layers could reduce the density and deteriorate the mobility of the 2DEG. The distance of ~0.5-0.9 μm from the GaN:Fe buffer to the AlN/GaN interface is found to be optimal in terms of the 2DEG properties. Further improvement of the breakdown voltage and leakage current are proposed to be achieved by field-plate engineering and composite or co-doped GaN:Fe/GaN:C buffer layer.

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References
[1] Chen J-T, Persson I, Nilsson D, Hsu C-W, Palisaitis J, Forsberg U, Persson P O Å and Janzén E 2015 Room-temperature mobility above 2200 cm$^2$/V·s of two-dimensional electron gas in a sharp-interface AlGaN/GaN heterostructure Appl. Phys. Lett. 106 251601
[2] Hubbard S, Zhao G, Pavlidis D, Sutton W and Cho E 2005 High-resistivity GaN buffer templates and their optimization for GaN-based HFETs J. Cryst. Growth 284 297–305
[3] Lampert M A and Mark P 1970 Current injection in solids (New York: Academic Press)
[4] Song C, Yang X, Ji P, Tang J, Hu A, Feng Y, Lin W, Ge W, Yang Z, Xu F and Shen B 2019 Role of electron injection on vertical leakage in GaN-on-Si epitaxial layers Superlattices Microstruct. 128 199–203
[5] Weimann N G, Eastman L F, Doppalapudi D, Ng H M and Moustakas T D 1998 Scattering of electrons at threading dislocations in GaN J. Appl. Phys. 83 3656–9
[6] Besendörfer S, Meissner E, Lesnik A, Friedrich J, Dadgar A and Erlbacher T 2019 Methodology for the investigation of threading dislocations as a source of vertical leakage in AlGaN/GaN-HEMT heterostructures for power devices J. Appl. Phys. 125 095704
[7] Jena D, Gossard A C and Mishra U K 2000 Dislocation scattering in a two-dimensional electron gas Appl. Phys. Lett. 76 1707–9
[8] Bougioua Z, Moerman I, Sharma N, Wallis R, Cheyns J, Jacobs K, Thrush E, Considine L, Beanland R, Farvacque J-L and Humphreys C 2001 Material optimisation for AlGaN/GaN HFET applications J. Cryst. Growth 230 573–8
[9] Tang H, Webb J, Bardwell J, Rolfe S and Macelwee T 2000 Reproducibility of growing AlGaN/GaN high-electron-mobility-transistor heterostructures by molecular-beam epitaxy Solid-State Electron. 44 2177–82
[10] Li X, Danielsson Ö, Pedersen H, Janzén E and Forsberg U 2015 Precursors for carbon doping of
GaN in chemical vapor deposition J. Vac. Sci. Technol., B, 33 021208

[11] Zhang R and Kuech T F 1998 Photoluminescence of carbon in situ doped GaN grown by halide vapor phase epitaxy Appl. Phys. Lett. 72 1611–3

[12] Tang H, Webb J B, Bardwell J A, Raymond S, Salzman J and Uzan-Saguy C 2001 Properties of carbon-doped GaN Appl. Phys. Lett. 78 757–9

[13] Hikosaka T, Koide N, Honda Y, Yamaguchi M and Sawaki N 2006 p-type conduction in a C-doped (1-101)GaN grown on a 7-degree-off oriented (001) Si substrate by selective MOVPE Phys. Status Solidi C 3 1425–8

[14] Armitage R, Yang Q, Feick H and Weber E 2004 Evaluation of CCl4 and CS2 as carbon doping sources in MBE growth of GaN J. Cryst. Growth 263 132–42

[15] Green D S, Mishra U K and Speck J S 2004 Carbon doping of GaN with CBr4 in radio-frequency plasma-assisted molecular beam epitaxy J. Appl. Phys. 95 8456–62

[16] As D J and Köhler U 2001 Carbon - an alternative acceptor for cubic GaN J. Phys.: Condens. Matter 13 8923–9

[17] Birkle U, Fehrer M, Kirchner V, Einfeldt S, Hommel D, Strauf S, Michler P and Gutowski J 1998 Studies on Carbon as Alternative P-Type Dopant for Gallium Nitride MRS Proc. 537

[18] Wright A F 2002 Substitutional and interstitial carbon in wurtzite GaN J. Appl. Phys. 92 2575–85

[19] Piotrzkowski R, Zajac M, Litwin-Staszewska E and Bockowski M 2020 Self-compensation of carbon in HVPE-GaN:C Appl. Phys. Lett. 117 012106

[20] Armitage R, Yang Q, Feick H, Park Y and Weber E R 2002 Electrical and Optical Properties of Carbon-Doped GaN Grown by MBE on MOCVD GaN Templates Using a CCl4 Dopant Source MRS Proc. 719

[21] Kawaniishi, H., 2017. Method Of Fabricating A P Type Nitride Semiconductor Layer Doped With Carbon. U.S. Patent 9,705,287.

[22] Uren M J, Moreke J and Kuball M 2012 Buffer Design to Minimize Current Collapse in GaN/AlGaN HFETs IEEE Trans. Electron Devices 59 3327–33

[23] Bisi D, Meneghini M, Hove M V, Marcon D, Stoffels S, Wu T-L, Decoutere S, Meneghesso G and Zanon E 2015 Trapping mechanisms in GaN-based MIS-HEMTs grown on silicon substrate Phys. Status Solidi A 212 1122–9

[24] Lundin W V, Zavarin E E, Brunkov P N, Yagovkina M A, Sakharov A V, Sinitsyn M A, Ber B Y, Kazantsev D Y and Tsatsulnikov A F 2016 Semi-insulating GaN:C epilayers grown by metalorganic vapor phase epitaxy using propane as a carbon source Tech. Phys. Lett. 42 539–42

[25] Tsuchiya T, Terano A and Mochizuki K 2016 Thick (>20 µm) and high-resistivity carbon-doped GaN-buffer layers grown by metalorganic vapor phase epitaxy on n-type GaN substrates Jpn. J. Appl. Phys. 55

[26] Lundin W V, Sakharov A V, Zavarin E E, Zakgeim D A, Lundina E Y, Brunkov P N and Tsatsulnikov A F 2019 Insulating GaN Epilayers Co-Doped with Iron and Carbon Tech. Phys. Lett. 45 723–6

[27] Chen F, Sun S, Deng X, Fu K, Yu G, Song L, Hao R, Fan Y, Cai Y and Zhang B 2017 High-resistivity unintentionally carbon-doped GaN layers grown by metalorganic chemical vapor deposition AIP Adv. 7 125018

[28] Wickenden A, Koleske D, Henry R, Twigg M and Fatemi M 2004 Resistivity control in unintentionally doped GaN films grown by MOCVD J. Cryst. Growth 260 54–62

[29] Heikman S, Keller S, Mates T, Denbaars S and Mishra U 2003 Growth and characteristics of Fe-doped GaN J. Cryst. Growth 248 513–7

[30] Balmer R S, Soley D E J, Simons A J, Mace J D, Koker L, Jackson P O, Wallis D J, Uren M J and Martin T 2006 On the incorporation mechanism of Fe in GaN grown by metal-organic vapour phase epitaxy Phys. Status Solidi C 3 1429–34

[31] Polyakov A Y and Lee I-H 2015 Deep traps in GaN-based structures as affecting the
performance of GaN devices Mater. Sci. Eng., R 94 1–56
[32] Bougrioua Z, Azize M, Lorenzini P, Lautig M and Haas H 2005 Some benefits of Fe doped less dislocated GaN templates for AlGaN/GaN HEMTs grown by MOVPE Phys. Status Solidi A 202 536–44
[33] Leone S, Benkelhila F, Kirste L, Manz C, Mueller S, Quay R and Stadelmann T 2017 Suppression of Iron Memory Effect in GaN Epitaxial Layers Phys. Status Solidi B 255 1700377
[34] Ishiguro T, Yamada A, Kotani J, Nakamura N, Kikkawa T, Watanabe K and Imanishi K 2013 New Model of Fe Diffusion in Highly Resistive Fe-Doped Buffer Layer for GaN High-Electron-Mobility Transistor Jpn. J. Appl. Phys. 52
[35] Soman R, Raghavan S and Bhat N 2019 An in situ monitored and controlled etch process to suppress Mg memory effects in MOCVD GaN growth on Si substrate Semicond. Sci. Technol. 34 125011
[36] Agarwal A, Tahhan M, Mates T, Keller S and Mishra U 2017 Suppression of Mg propagation into subsequent layers grown by MOCVD J. Appl. Phys. 121 025106
[37] Feng Z, Liu B, Yuan F, Yin J, Liang D, Li X, Feng Z, Yang K and Cai S 2007 Influence of Fe-doping on GaN grown on sapphire substrates by MOCVD J. Cryst. Growth 309 8–11
[38] Yamamoto T, Sazawa H, Nishikawa N, Kucchi M, Ide T, Shimizu M, Inoue T and Hata M 2013 Reduction in Buffer Leakage Current with Mn-Doped GaN Buffer Layer Grown by Metal Organic Chemical Vapor Deposition Jpn. J. Appl. Phys. 52
[39] Mei F, Wu K M, Pan Y, Han T, Liu C, Gerlach J W and Rauschenbach B 2008 Structural and optical properties of Cr-doped semi-insulating GaN epilayers Appl. Phys. Lett. 93 113507
[40] Kuznetsov N I, Nikolaev A E, Zubrilov A S, Melnik Y V and Dmitriev V A 1999 Insulating GaN:Zn layers grown by hydride vapor phase epitaxy on SiC substrates Appl. Phys. Lett. 75 3138–40
[41] Katzer D, Storm D, Binari S, Roussos J, Shanabrook B and Glaser E 2003 Molecular beam epitaxy of beryllium-doped GaN buffer layers for AlGaN/GaN HEMTs J. Cryst. Growth 251 481–6
[42] Storm D, Katzer D, Deen D, Bass R, Meyer D, Roussos J, Binari S, Paskova T, Preble E and Evans K 2010 Proximity effects of beryllium-doped GaN buffer layers on the electronic properties of epitaxial AlGaN/GaN heterostructures Solid-State Electron. 54 1470–3
[43] Ko K, Lee K, So B, Heo C, Lee K, Kwak T, Han S-W, Cha H-Y and Nam O 2016 Mg-compensation effect in GaN buffer layer for AlGaN/GaN high-electron-mobility transistors grown on 4H-SiC substrate Japanese J. Appl. Phys. 56 015502
[44] Wang Y, Yu N, Deng D, Li M, Sun F and Lau K 2010 Improved breakdown voltage of AlGaN/GaN HEMTs grown on Si substrates using partially Mg-doped GaN buffer layer by MOCVD Sci. China Phys., Mech. Astron. 53 1578–81
[45] Silvestri M, Uren M J and Kuball M 2013 Iron-induced deep-level acceptor center in GaN/AlGaN high electron mobility transistors: Energy level and cross section Appl. Phys. Lett. 102 073501
[46] Farahmand M, Garetto C, Bellotti E, Brennan K, Goano M, Ghillino E, Ghione G, Albrecht J and Ruden P 2001 Monte Carlo simulation of electron transport in the III-nitride wurtzite phase materials system: binaries and ternaries IEEE Trans. Electron Devices 48 535–42
[47] Chen S and Wang G 2008 High-field properties of carrier transport in bulk wurtzite GaN: A Monte Carlo perspective J. Appl. Phys. 103 023703
[48] Selberherr S 1984 Analysis and simulation of semiconductor devices (Wien: Springer)
[49] Karmalkar S and Mishra U 2001 Enhancement of breakdown voltage in AlGaN/GaN high electron mobility transistors using a field plate IEEE Trans. Electron Devices 48 1515–21
[50] Neha, Kumari V, Gupta M and Saxena M 2018 Breakdown Voltage Analysis of Different Field Plate AlGaN/GaN HEMTs: TCAD based Assessment 2018 IEEE Electron Devices Kolkata Conference (EDKCON)
[51] Liao B, Zhou Q, Qin J and Wang H 2019 Simulation of AlGaN/GaN HEMTs’ Breakdown Voltage Enhancement Using Gate Field-Plate, Source Field-Plate and Drain Field Plate Electron. 8 406

[52] Hanawa H, Onodera H, Nakajima A and Horio K 2014 Numerical Analysis of Breakdown Voltage Enhancement in AlGaN/GaN HEMTs With a High-\(k\) Passivation Layer IEEE Trans. Electron Devices 61 769–75