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Floating Body Effects in Carbon Doped GaN HEMTs

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***Abstract* — GaN power HEMTs use carbon doped buffers to deliver high breakdown voltage and off-state low leakage; however these devices are highly vulnerable to dynamic dispersion. Carbon doped GaN has its Fermi level pinned 0.9eV above the valence band and in equilibrium would be isolated from the 2DEG by a reverse biased PN junction and hence would be electrically floating. In reality leakage across that junction and charge storage in the compensated deep acceptors controls the buffer potential, the dynamic on-resistance dispersion and the gate-drain breakdown voltage. We discuss experiment and simulation that supports the model that controlling leakage to the floating buffer is critical for power device operation.**

Keywords—power switching, FET, dynamic Ron, current-collapse, breakdown voltage

I. INTRODUCTION

AlGaN/GaN-on-Si HEMTs are presently being actively developed for power applications motivated by the basic material benefits of high breakdown field and high mobility. GaN HEMT technology was first developed for RF power amplifier applications where it is now successfully displacing the incumbent GaAs based technologies. These RF devices have now evolved to largely use a common architecture based around field-plates to control the peak surface electric field, and an iron doped GaN buffer to render the material semi-insulating and control the drain leakage that is a problem in short-channel devices [1]. This solution works well for typical RF power amplifiers working with drain voltages of perhaps 48V. However when this successful device solution was applied to high-voltage power switches, which are required to sustain off-state voltages of typically 600V as well any necessary margin, it was found that the off-state leakage was too high and equally importantly the breakdown voltage was too low. It was found that an alternative deep-level dopant could be used to enhance the breakdown voltage, and so the dopant of choice for semi-insulating GaN for power applications has become carbon. Unfortunately it was also found that carbon doped transistors although delivering excellent breakdown voltage were also very susceptible to dynamic Ron dispersion (DRon), also referred to as current-collapse [2]. DRon is a temporary increase in the device on-resistance after switching from the off-state to the on-state and can increase the on-resistance even by factors of 10, whereas an acceptable increase for application acceptance is probably less than 10%. Fabricating a device that simultaneously delivers high breakdown voltage and low DRon is currently one of the biggest challenges facing power GaN technology and the subject of intensive research worldwide.

Here we review the work in our group which has aimed to explain the origin of the high breakdown voltage and vulnerability to DRon in carbon doped transistors. We will show that the underlying cause is the trap energy level and its impact on the current transport in the semi-insulating buffer. Both iron and carbon have deep acceptor levels in the GaN bandgap, however the Fe acceptor level is about 0.5-0.7eV below the conduction band whereas the C acceptor level is 0.9eV above the valence band. The consequence is that in contrast to Fe which is n-type and hence resistively linked to the 2DEG, the GaN:C buffer is weakly p-type and so is isolated from the 2DEG by a PN junction. Hence the semi-insulating GaN:C buffer region is electrically floating relative to the electron channel. In this paper we discuss the evidence for this assignment and discuss the critical impact of the leakage path between this floating buffer region and the 2DEG channel on breakdown and DRon.

II. CARBON DOPED GAN/ALGAN HEMTS

A. *The "ideal" C-doped HEMT*

Carbon doped GaN generates semi-insulating material with excellent breakdown strength, however there have been reports of strong DRon being observed especially when the carbon is located in the region of the 2DEG [3, 4]. Carbon impurities are always present as a contaminant in MOCVD grown GaN, but modifying the growth conditions or adding an external source can increase the concentration above 10^{19}cm^{-3} [5]. The carbon can be substituted on either the Ga or N site and can form a variety of complexes, with each species having different trap characteristics. Hence SIMS profiles of C density can only place an upper limit on the density of electrically active C and the actual trap energy levels may well vary with growth conditions. Many energy levels for the carbon impurity have been reported but the most convincing model seems to be that of Lyons [6] who reported that most C is expected to be on the N site, which has a donor level just above the valence band and an acceptor level 0.9eV above the valence band. It is this latter acceptor level which, when partly compensated by a smaller density of donors such as oxygen impurities with energy level close to the conduction band, will pin the Fermi level close to 0.9eV above the valence band in the bulk of the GaN. Measurements using a dynamic transconductance technique for a C-doped HEMT gave an activation energy of 0.86eV in good

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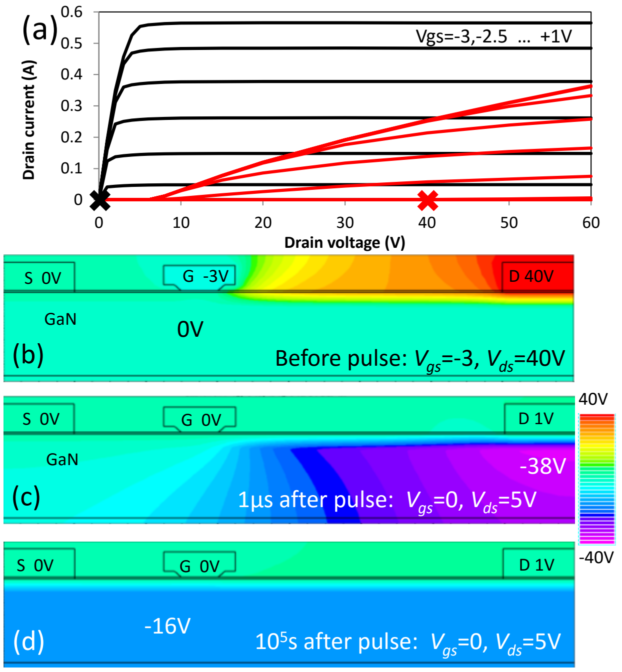

Fig. 1. (a) Simulated pulse IV characteristic of an "ideal" C-doped RF HEMT for 1µs pulses. Black line pulsed from Vgs=0, Vds=0V to each point on the IV characteristic, red line pulsed from Vds=40V, Vgs=−3V. (b to d) Simulated potential distributions. The epitaxial layer structure consists of an AlGaN barrier (too thin to distinguish), an undoped GaN layer of thickness 0.2µm, a carbon doped GaN layer of density $10^{18}cm^{-3}$, grown on an insulating SiC wafer; (b) is in off-state at Vg=−3, Vd=40V, (c) 1µs and (d) 10^5s after switching to the on-state at Vgs=0, Vds=1V.

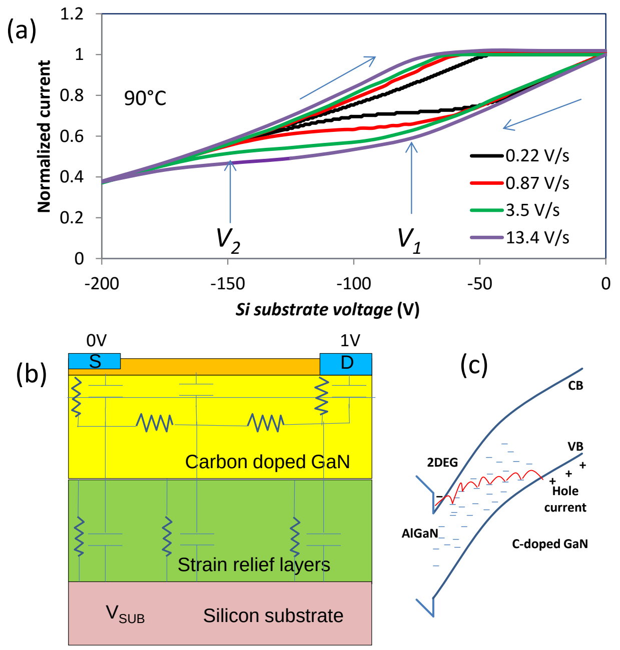

Fig. 2 (a) Silicon substrate bias sweep with 1V between 60µm spacing front contacts at the indicated sweep rates. Varying the ramprate shows dispersion indicating trapping in the buffer. (b) The equivalent circuit of the structure overlaid on the generic layer structure indicates the various leakage paths and capacitances. (c) TAT mechanism for vertical leakage.

agreement with this energy level [7]. Here we will assume that this energy level is correct and use it in our discussion.

Any GaN transistor requires a confining potential to keep the electrons in the channel and in single heterojunction GaN/AlGaN devices this is provided by the presence of ionized acceptors in the buffer [8]. In the case of iron doped GaN RF transistors, where the acceptor level is located about 0.7eV below the conduction band, simulation of pulse operation of a transistor (which corresponds to the DRon measurement) gives a result which is remarkably close to experiment with only a small increase in DRon [9]. However for the C-doped transistor, where the Fermi level in the bulk of the GaN:C is 0.9eV above the valence band, simulation under pulse conditions always gave very large DRon. Figure 1a shows such a simulation where the Id-Vds characteristic is plotted when pulsed from two different quiescent off-state biases. The full lines are pulsed from Vgs=0, Vds=0V corresponding to no charge trapped in the device, and the red lines are from the off-state bias of Vds=40V, Vg=-3V where an equilibrium trapped charge will be present. When pulsed from the off-state there is a dramatic increase in dynamic on-resistance (DRon) and a drop in saturation current [9]. The buffer potential before and after switching from the off to the on-state is shown in Fig. 1b-d. The key point in understanding these plots is that the C-doped GaN buffer is very weakly p-type (with a resistivity of $>10^{13}$ Ohm·cm and hole density of only $\sim10^5cm^{-3}$). Thus in an ideal device where the device has time to reach an equilibrium off-state trapped charge distribution, a reverse biased P-N junction will form under the 2DEG (Fig. 1b) which will isolate the buffer from the 2DEG and allow charge to be stored for long periods. Immediately after switching the device on (Fig. 1c) the stored negative depletion charge forces the buffer potential negative pinching off the channel and causing the increase in DRon seen in Fig. 1a. If we hold the device in the on-state the simulated device does not fully recover. Even after 10^5 s (Fig. 1d), slow redistribution of free holes within the isolated buffer has achieved a back-gating equipotential of −16V which would result in an increased DRon. Essentially the C-doped GaN behaves as an electrically floating region which because of its wide bandgap will never reach equilibrium. However, as we shall see later in reality some C-doped devices can have moderate or low DRon strongly suggesting that this simple idealized point defect floating-body model is incomplete and does not adequately describe the behavior of these devices.

B. Impact of extended defects on vertical transport in C-doped HEMTs

In reality, GaN is a highly defective material and may have more than 10^9 cm^{-2} of threading dislocations. In GaN based light emitting diodes reverse P-N junction leakage occurs by a trap-assisted process which can have an activation energy far lower than the bandgap and can be as little as a few hundred meV [10]. There is strong evidence that this leakage occurs along threading screw and mixed dislocations [11-13]. In C-doped GaN HEMTs the dislocations run vertically through the structure and will pass through the P-N junction which should form under the 2DEG. Hence it is important to understand their impact on leakage and charge storage in the floating buffer. However the leakage as a function of depth in typical GaN-on-

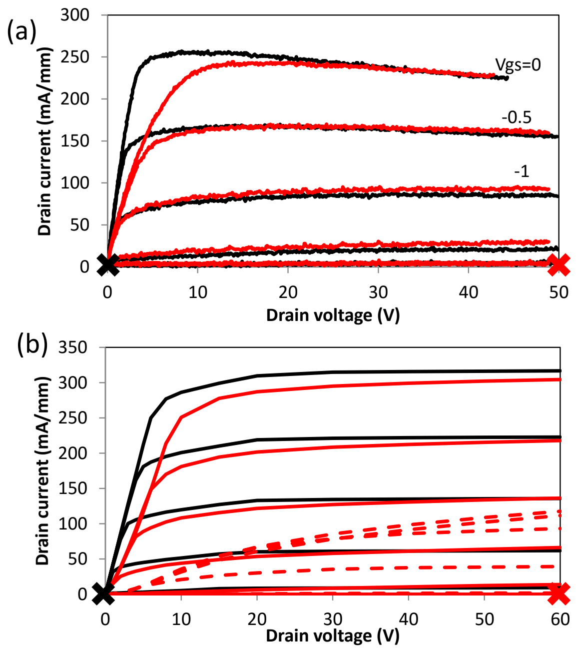

Fig. 3 (a) Measured pulse IV characteristic for a C-doped GaN-on-Si HEMT. Quiescent biases: black line Vg=0, Vd=0V, red line Vg=-3, Vd=50V. (b) Simulated pulse I-V for a C-doped device. Solid lines have the source and drain shorted to the C-doped buffer to represent the effect of leaky dislocations, the dashed line has the C-doped buffer floating.

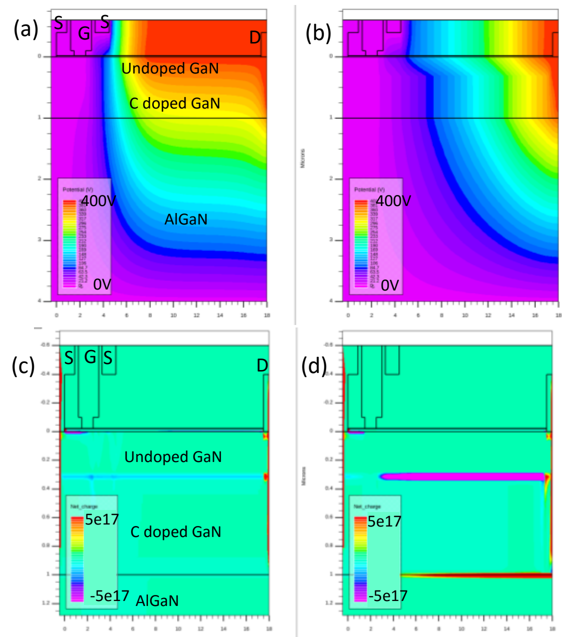

Fig. 4. C-doped power transistor with leakage paths under the source and drain showing the potential distribution in the OFF-state at V_{DS}=400V (a,b) and the trapped charge (c,d). (a,c) shows the distribution 1μs after switching from ON to OFF so there is insufficient time for any charge to be trapped, (b,d) shows the equilibrium OFF state with negative and positive charge layers performing a RESURF function.

Si epitaxy is difficult to monitor directly due to the existence of multiple highly resistive layers, heterojunctions associated with Al containing layers, and strain-relief and nucleation structures. Recently we found that the leakage properties of the key layers in the C-doped HEMT can be separately distinguished using a substrate bias ramp technique [7, 14]. The measurement technique is based on using the Si substrate as a back gate to control the conductivity of the 2DEG, an approach which has previously been used to undertake DLTS and deep acceptor density measurements [15, 16]. Charge trapping in the buffer during back biasing is time dependent and leads to dispersion when varying the ramprate which when compared with an equivalent circuit representation of the epitaxial layer structure allows leakage in each layer of the device to be identified. Figure 2a shows an example where the voltages V_1 and V_2 respectively correspond in this case to the voltages at which vertical leakage becomes comparable to the displacement current in the upper (C-doped GaN) and lower (strain relief layers) of the structure [14]. Monitoring these voltages as a function of ramprate and temperature allows an I-V characteristic to be extracted for each layer using the equivalent circuit shown in Fig. 2b. In this particular epitaxial layer structure it was found that there was a vertical leakage path between the 2DEG and the C-doped GaN with an activation energy of ~0.7eV which was consistent with a Poole-Frenkel conduction law. Leakage through the strain relief layers occurred at much higher field and again could be described by a Poole-Frenkel law. Charge flow within the C-doped layer could also be distinguished with an activation energy of 0.86eV fully consistent with Fermi level pinning at the C_N acceptor level [6]. Measurements using the substrate ramp technique have now been carried out in our group on epitaxial layer structures from many sources and although they show very different detailed leakage behavior, one common factor that is seen is a non-Ohmic leakage from the 2DEG to the carbon doped layer. In Figure 2a this leakage shows a clear signature between voltages V_1 and V_2 and corresponds to a build-up of positive charge in the buffer region. Given the sign of the applied electric field this requires that holes flow into the GaN:C from the 2DEG. In GaN LEDs it has been proposed that the process involves a trap-assisted-tunneling mechanism along the dislocations as shown in Fig. 2c [17]. It is entirely to be expected that this mechanism will also be occurring in the reverse biased junction between the 2DEG and the p-type GaN:C although other leakage mechanisms are also possible.

C. Suppression of dynamic Ron dispersion by vertical leakage

The existence of the leakage path between the 2DEG channel and the semi-insulating carbon doped buffer can have a dramatic effect on the DRon. Simulating this vertical leakage path through the reverse biased PN junction, which presumably occurs along only a small proportion of the high density of threading dislocations, is not straightforward. So a simple solution was adopted which captures the basic behavior. A small heavily P++ doped region was placed under the source and drain contacts and which acted to short the Ohmic contacts to the otherwise floating P-type buffer [7, 18]. The effect is to prevent the build-up of an equipotential in the buffer in the off-state (as seen in Figure 1b) or a floating potential in the buffer in the on-state (as seen in Fig. 1d). The result of such a simulation is shown in Fig. 3 together with the experimental pulse I-V for a comparable C-doped device. When a leakage path is included a moderate DRon is predicted similar to

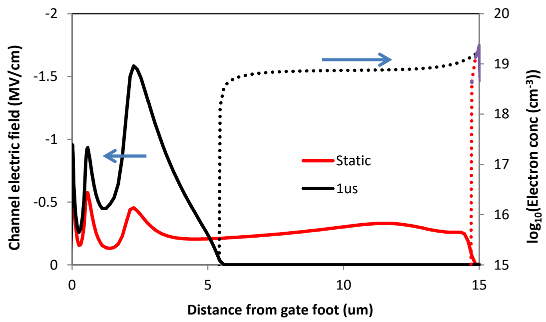

Fig. 5. Electric field (full lines) and electron concentration (dashed lines) in the channel of the simulated device shown in Fig. 4 after switching from ON to OFF with V_{DS}=400V. The black lines show 1μs after switching OFF when there is no significant charge trapping in the buffer. The red lines show the situation once equilibrium in the trap states has been established in the OFF state. In equilibrium the RESURF effect spreads the field across the entire G-D gap.

experiment [18]. If the buffer is allowed to float then as also seen in Fig. 1b, the magnitude of DRon is dramatically increased.

It seems that the dispersive behavior of C-doped devices is intimately linked to the leakage behavior of the extended defects. Hence these C-doped devices require a balance between vertical leakage and DRon. Understanding and controlling the leakage along extended defects is key to obtaining high performance power devices. This is especially important since dislocations have been linked to the reliability of GaN HEMTs[19].

D. Impact of leakage and C doping on breakdown

So let us consider the location of the charge trapping responsible for DRon during an off-state drain bias when there is a vertical leakage path through the GaN, and its impact on breakdown [20]. Figure 4 shows a 2D transient simulation of a power device incorporating such a leakage path under the source and drain contacts. Immediately after turning the device off (Fig. 4a,c), the buffer behaves as a dielectric so there is no charge storage and the 2DEG is depleted only close to the gate. However once the device attains equilibrium after as much as 10000s, the compensated resistive GaN:C layer acts as a back-gate to the 2DEG with negative ionized acceptors and positive ionized compensating donors at its upper and lower surfaces respectively (Fig. 4b,d). This trapped charge acts as a reduced surface electric field structure (RESURF) and spreads the field more uniformly between gate and drain. One consequence is that the 2DEG is depleted over the entire gate to drain gap reducing the electric field. The simulated 2DEG density and lateral electric field is shown in Fig. 5 where it can be seen that the consequence of the trapped charge is a reduction of the field from 1.6 MV/cm to only 0.6 MV/cm. In reality the distribution of leakage paths will be somewhat different from the limiting case simulated but will nevertheless still generate a spreading of the field. This reduction in field helps to explain why GaN:C has been adopted for high voltage power devices since it offers a dramatic increase in drain voltage compared to an iron doped GaN transistor where this RESURF effect cannot occur. Unfortunately the trapped charge will also result in a DRon effect so there will ultimately be a trade-off between breakdown, leakage and DRon.

III. Conclusions

Carbon doped GaN has been widely adopted for power device applications since it has been shown to deliver high breakdown voltage and low off-state leakage. We have shown that this benefit arises as a direct consequence of the C deep-acceptor energy level which renders the material semi-insulating but nevertheless weakly p-type. The consequence is that slow charge storage can occur in the floating buffer region via vertical and lateral leakage paths, with the dynamics of this charge storage determined by the leakage paths and not just by the actual traps themselves. Another consequence is that the magnitude of dynamic Ron dispersion measurements is a function of the timescales over which the measurement is undertaken. It also follows that optimization of device performance requires full control of leakage paths.

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References

[1] Y. F. Wu, A. Saxler, M. Moore, R. P. Smith, S. Sheppard, P. M. Chavarkar, T. Wisleder, U. K. Mishra, and P. Parikh, "30-W/mm GaN HEMTs by field plate optimization," *IEEE Elec. Dev. Lett.*, vol. 25, pp. 117-119, Mar 2004.

[2] J. Wuerfl, O. Hilt, E. Bahat-Treidel, R. Zhytnytska, P. Kotara, F. Brunner, O. Krueger, and M. Weyers, "Techniques towards GaN power transistors with improved high voltage dynamic switching properties," *International Electron Devices Meeting (IEDM)*, 2013, pp. 6.1.1-6.1.4.

[3] C. Poblenz, P. Waltereit, S. Rajan, S. Heikman, U. K. Mishra, and J. S. Speck, "Effect of carbon doping on buffer leakage in AlGaN/GaN high electron mobility transistors," *J. Vac. Sci. Technol.*, vol. B22, p. 1145, 2004.

[4] E. Bahat-Treidel, F. Brunner, O. Hilt, E. Cho, J. Wurfl, and G. Trankle, "AlGaN/GaN/GaN:C back-barrier HFETs with breakdown voltage of over 1 kV and low R_{ON} x *A*," *IEEE Trans. Elec. Dev.*, vol. 57, pp. 3050-3058, Nov 2010.

[5] X. Li, O. Danielsson, H. Pedersen, E. Janzen, and U. Forsberg, "Precursors for carbon doping of GaN in chemical vapor deposition," *Journal of Vacuum Science & Technology B*, vol. 33, Mar 2015.

[6] J. L. Lyons, A. Janotti, and C. G. Van de Walle, "Carbon impurities and the yellow luminescence in GaN," *Appl. Phys. Lett.*, vol. 97, p. 152108, 2010.

[7] M. J. Uren, M. Silvestri, M. Cäsar, G. A. M. Hurkx, J. A. Croon, J. Šonský, and M. Kuball, "Intentionally Carbon-Doped AlGaN/GaN HEMTs: The Necessity for Vertical Leakage Paths," *IEEE Elec. Dev. Lett.*, vol. 35, pp. 327-329, 2014.

[8] M. J. Uren, K. J. Nash, R. S. Balmer, T. Martin, E. Morvan, N. Caillas, S. L. Delage, D. Ducatteau, B. Grimbert, and J. C. De Jaeger, "Punch-through in short-channel AlGaN/GaN HFETs," *IEEE Trans. Elec. Dev.*, vol. 53, pp. 395-398, 2006.

[9] M. J. Uren, J. Möreke, and M. Kuball, "Buffer design to minimize current collapse in GaN/AlGaN HFETs," *IEEE Trans. Elec. Dev.*, vol. 59, pp. 3327-3333, 2012.

[10] D. V. Kuksenkov, H. Temkin, A. Osinsky, R. Gaska, and M. A. Khan, "Origin of conductivity and low-frequency noise in reverse-biased GaN p-n junction," *Appl. Phys. Lett.*, vol. 72, pp. 1365-1367, Mar 1998.

[11] J. W. P. Hsu, M. J. Manfra, D. V. Lang, S. Richter, S. N. G. Chu, A. M. Sergent, R. N. Kleiman, L. N. Pfeiffer, and R. J. Molnar, "Inhomogeneous spatial distribution of reverse bias leakage in GaN Schottky diodes," *Appl. Phys. Lett.*, vol. 78, pp. 1685-1687, Mar 19 2001.

[12] M. Meneghini, A. Tazzoli, G. Mura, G. Meneghesso, and E. Zanoni, "A review on the physical mechanisms that limit the reliability of GaN-based LEDs," *IEEE Trans. Elec. Dev.*, vol. 57, pp. 108-118, 2010.
[13] X. A. Cao, J. A. Teetsov, F. Shahedipour-Sandvik, and S. D. Arthur, "Microstructural origin of leakage current in GaN/InGaN light-emitting diodes," *J. Crystal Growth*, vol. 264, pp. 172-177, 2004.
[14] M. J. Uren, M. Cäsar, M. A. Gajda, and M. Kuball, "Buffer Transport Mechanisms in Intentionally Carbon Doped GaN Heterojunction Field Effect Transistors " *Appl. Phys. Lett.*, vol. 104, p. 263505, 2014.
[15] M. Marso, M. Wolter, P. Javorka, P. Kordos, and H. Luth, "Investigation of buffer traps in an AlGaN/GaN/Si high electron mobility transistor by backgating current deep level transient spectroscopy," *Appl. Phys. Lett.*, vol. 82, pp. 633-635, Jan 27 2003.
[16] M. J. Uren, D. Herbert, T. Martin, B. T. Hughes, J. Birbeck, R. Balmer, A. J. Pidduck, and S. K. Jones, "Back Bias Effects in AlGaN/GaN HFETs," *Physica Status Solidi (A) Applied Research*, vol. 188, pp. 195-198, 2001.
[17] Q. F. Shan, D. S. Meyaard, Q. Dai, J. Cho, E. F. Schubert, J. K. Son, and C. Sone, "Transport-mechanism analysis of the reverse leakage current in GaInN light-emitting diodes," *Appl. Phys. Lett.*, vol. 99, p. 253506, Dec 2011.
[18] M. J. Uren, M. Silvestri, M. Cäsar, J. W. Pomeroy, G. A. M. Hurkx, J. A. Croon, J. Šonský, and M. Kuball, "Need for Defects in Floating-Buffer AlGaN/GaN HEMTs," *CS-MANTECH*, Denver, 2014, pp. 317-319.
[19] M. Tapajna, S. W. Kaun, M. H. Wong, F. Gao, T. Palacios, U. K. Mishra, J. S. Speck, and M. Kuball, "Influence of threading dislocation density on early degradation in AlGaN/GaN high electron mobility transistors," *Appl. Phys. Lett.*, vol. 99, p. 223501, Nov 2011.
[20] M. J. Uren, M. Caesar, S. Karboyan, P. Moens, P. Vanmeerbeek, and M. Kuball, "Electric Field Reduction in C-Doped AlGaN/GaN on Si High Electron Mobility Transistors," *IEEE Elec. Dev. Lett.*, vol. 36, pp. 826-828, 2015.