

Impact of Carbon Doping on Avalanche Breakdown in AlGaIn/GaN HEMTs

In this chapter, physics behind improvement in breakdown voltage of AlGaIn/GaN HEMTs with carbon(C) doping of GaN buffer is discussed with detailed insight into electric field relaxation and delayed avalanche action for the very first time [Joshi *et al.* 2019a]. Presence of C as acceptor traps and self-compensating acceptor/donor traps in GaN buffer is discussed with respect to its impact on avalanche breakdown. A detailed account is presented on the influence of C, behaving as donor and/or acceptor traps, on electric field relaxation and avalanche generation. The physical insight thus gained is then utilized to discuss design parameters related to carbon doped buffer. Design parameters such as undoped channel thickness and relative trap concentration induced by carbon doping are discussed with respect to the performance metrics of breakdown voltage, leakage current, sheet charge density and ON-resistance [Joshi *et al.* 2019a].

4.1 INTRODUCTION

Buffer resistivity is often believed to be a key design parameter to maximize breakdown voltage (V_{BD}) of AlGaIn/GaN HEMTs. Being unintentionally n-type doped, doping of iron (Fe)/carbon (C) is commonly employed to control GaN buffer resistivity, which in turn introduce trap sites in GaN buffer [Lyons *et al.* 2010, Uren *et al.* 2012, Lyons *et al.* 2014, Verzellesi *et al.* 2014a, Uren *et al.* 2015, Chini *et al.* 2016]. C doping in GaN buffer is widely recognized as an effective method to increase buffer breakdown voltage [Bahat-Treidel *et al.* 2010]. C in GaN can replace either Ga or N and behave as either donor or acceptor trap site [Lyons *et al.* 2014], respectively. This has led to an active debate on the type of traps it introduces [Lyons *et al.* 2014, Verzellesi *et al.* 2014a, Chini *et al.* 2016], [Uren *et al.* 2012, Uren *et al.* 2015]. Different works have presented different models. In few works, C in GaN is proposed to behave as deep acceptor [Lyons *et al.* 2010, Lyons *et al.* 2014], while other works have modeled it in self-compensating configuration in which it can be present as deep acceptor as well as deep [Lyons *et al.* 2014] or shallow [Uren *et al.* 2012, Verzellesi *et al.* 2014a, Uren *et al.* 2015, Chini *et al.* 2016] donor. Study in [Verzellesi *et al.* 2014a] suggests C to be present as deep acceptor and compensating shallow donor traps in equal concentration. On the other hand, TCAD based study in [Chini *et al.* 2016] suggests that C in self-compensating configuration with equal donor and acceptor trap concentrations cannot result in experimentally observed current collapse behavior. Further, using density function theory (DFT) based calculations, it was suggested that the formation energy required for C to replace Ga in the standard growth conditions (n-type GaN with Ga-face) is very high, making it less probable for C to behave as donor trap site [Lyons *et al.* 2014].

While the impact of C-Doping, modeled as traps, on DC-RF dispersion of the device has been well explored [Uren *et al.* 2012, Uren *et al.* 2015, Chini *et al.* 2016], the mechanism behind delayed avalanche action or breakdown voltage improvement with C-Doping is not well understood. A TCAD based computational study of electric field relaxation resulting from C-Doping is presented in [Uren *et al.* 2015], which assumed trap concentration to be significantly lower than the C doping values while using a hole short placed between source/drain contacts and C-doped region. However, deeper insights towards electric field relaxation, which can potentially explain breakdown voltage improvement, is missing in earlier works. Moreover,

impact of acceptor traps and presence of both acceptor and donor type traps on avalanche effect is yet to be explored. Beside this, correlation between C-Doping and associated trap concentrations is missing in previous works. In this work, behavior of C-Doping as traps in GaN buffer is discussed in relation with its impact on breakdown voltage for the very first time. Section 4.2 explains the computational framework used in this work. Section 4.3 discusses modeling of C-Doping in different trap configurations and their impact on breakdown voltage. Section 4.4 presents a physical insight into the impact of traps on electric field distribution and avalanche breakdown in AlGaIn/GaN HEMT devices. Section 4.5 presents AlGaIn/GaN channel/buffer stack and C-doping co-design guideline for improved breakdown voltage while keeping the leakage current and on-resistance minimum. Finally, the work is concluded in Section 4.6.

4.2 COMPUTATIONAL FRAMEWORK

The computations in this work were done using Synopsys Sentaurus TCAD [Synopsys 2014] suite. Impact ionization was considered using the Chynoweth law [Chynoweth 1958]. Polarization induced fixed charges are considered at all the material interfaces to accurately estimate parasitic channels present in the device, as was reported in [Joshi *et al.* 2016]. Lattice & carrier temperature related calculations along with quantum correction were found to have negligible impact on breakdown voltage and hence were neglected in this work. Contacts with the channel were modeled as Schottky interfaces with lower work function of 4.1 eV to consider TiN alloy formation and N vacancies at the interface between contact and GaN buffer. Modeling aspects related to channel transport, mobility and sheet charge density were calibrated with experimental data according to framework described in our earlier work [Joshi *et al.* 2016].

The device architecture considered for modeling study is depicted in Fig. 4.1(a). Schottky-gated non-recessed devices are considered here to isolate any impact of gate geometry, accounting for only buffer induced effects on breakdown performance of the device. Fig. 4.1(b) depicts an excellent match between TCAD extracted breakdown trends and experimental data [Bahat-Treidel *et al.* 2010]. The excellent agreement between computational and experimental data as depicted in Fig. 4.1(b) is achieved by calibrating C-doping induced donor and acceptor trap concentrations. C-Doping induced traps and associated impact on avalanche breakdown of device with associated physics is discussed in the following sections. Moreover, donor type surface traps were considered at the AlGaIn surface/passivation layer interface with an activation energy of $E_C - 0.68$ eV [Bisi *et al.* 2013] and a constant concentration of $1.6 \times 10^{13} \text{ cm}^{-2}$. These surface traps are taken to compensate hole density on surface [Joshi *et al.* 2016] and the concentration value is selected to achieve the required sheet charge density (n_s) and gate leakage [Joshi *et al.* 2016].

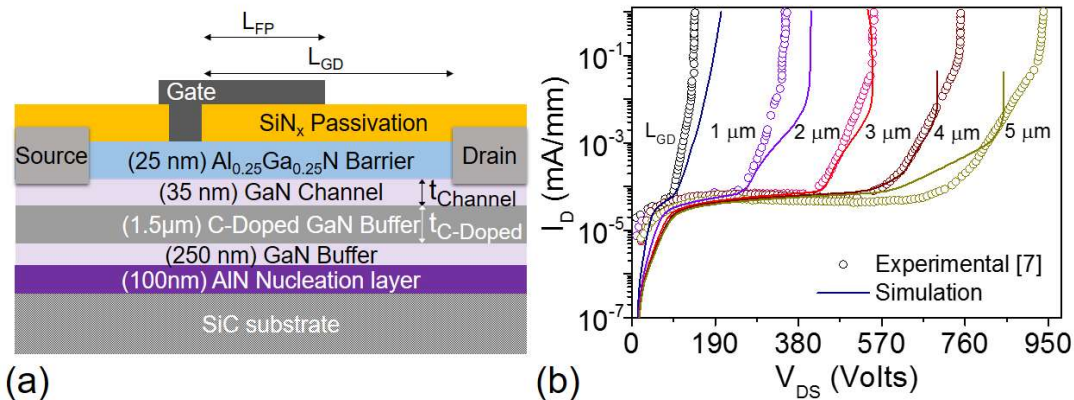


Figure 4.1: (a) Carbon doped AlGaIn/GaN HEMT considered in this work, as adapted from [Bahat-Treidel *et al.* 2010]. (b) Comparison of experimental [Bahat-Treidel *et al.* 2010] and TCAD computation based breakdown characteristics of C-doped device with $L_{FP} = 0.6 \mu\text{m}$.

4.3 C-DOPING VS. AVALANCHE BREAKDOWN: NATURE OF TRAPS

Device cross-section as shown in Fig. 4.1(a) is used for computations in this work. Following device parameters are kept constant at specified values until explicitly stated: source to gate distance = 1 μm , gate length = 0.7 μm , gate to drain distance (L_{GD}) = 5 μm , field plate length (L_{FP}) = 0.6 μm , t_{Channel} = 35 nm, $t_{\text{C-Doped}}$ = 1.5 μm . An unintentional (n-type) doping (UID) of $1 \times 10^{15} \text{ cm}^{-3}$ is considered in the GaN buffer. Modeling of C as traps and its impact on avalanche breakdown is discussed in the following sections. A uniform C-Doping is considered in the C-Doped GaN buffer region. Hence, the trap concentration induced by C-Doping will be considered as uniformly distributed in the $t_{\text{C-Doped}}$ thick GaN buffer region. In this section two possibilities are investigated: (1) C-doping to behave as acceptor traps [Lyons *et al.* 2014, Chini *et al.* 2016] and (2) C-doping in self-compensating mode where both acceptor and donor traps are considered simultaneously, however with different concentrations and trap energy.

4.3.1 Possibility 1: C-Doping as Acceptor Trap

As C is widely debated to behave as acceptor trap in GaN [Lyons *et al.* 2014, Chini *et al.* 2016], C-Doping in this section is modeled as deep acceptor traps with energy $E_{\text{V}} + 0.9 \text{ eV}$ [Lyons *et al.* 2010]. Impact of such an acceptor trap's concentration on breakdown voltage of AlGaIn/GaN HEMT device is depicted in Fig. 4.2(a).

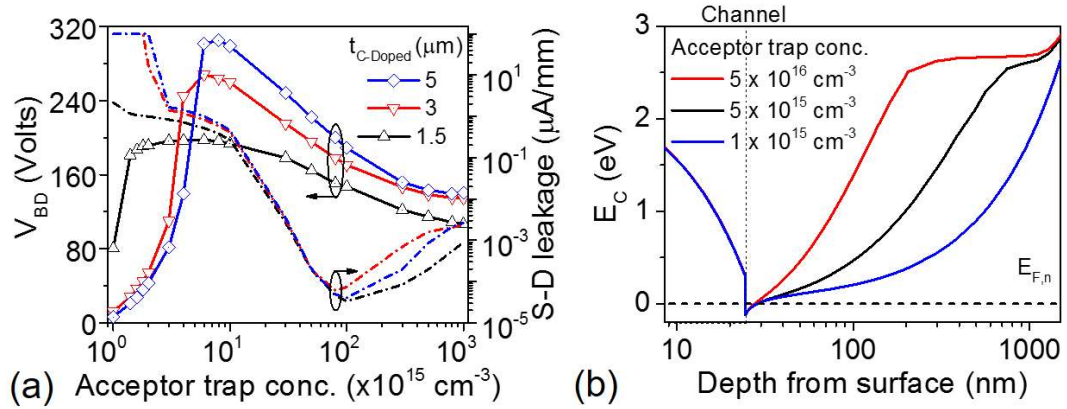


Figure 4.2: Impact of acceptor trap concentration, considered in the C-Doped region, on (a) breakdown voltage and leakage current, extracted at $V_{\text{DS}} = 50 \text{ V}$, in the device, and (b) Conduction band energy extracted along a vertical cut-line traversing from AlGaIn surface (0 nm) to GaN buffer.

It can be observed that breakdown voltage initially improves with acceptor trap concentration, saturates to a value at moderate concentrations and then starts decreasing with further increase in acceptor trap concentration. Moreover, the breakdown voltage was found to increase as the C-doped GaN buffer thickness was increased. This behavior can be explained as follows. As can be observed from energy band diagram shown in Fig. 4.2(b), Fermi level shifts away from conduction band edge with the introduction of C-doping. Thus, an increase in acceptor trap concentration in the GaN buffer makes the material intrinsic. This effectively increases the buffer resistivity, which suppresses the buffer leakage, as depicted in Fig. 4.2(a). This results in an improvement in breakdown voltage as acceptor trap concentration is increased initially, to a concentration greater than UID. However, as can be seen from Fig. 4.2(a), beyond a certain acceptor trap concentration, breakdown voltage falls dramatically, even when the leakage current continues to fall (or buffer resistivity continues to increase) with increasing acceptor trap concentration. In order to explain this effect, channel (lateral) and buffer (vertical) electric fields for different acceptor trap concentrations are extracted along cutline A - A' and B - B' as shown in Fig. 4.3(a). A comparison of lateral electric field as shown in Fig. 4.3(b) indicates the avalanche hot spot to be located near the drain edge for all the cases. It should be noted that the field is

extracted when drain voltage = breakdown voltage, which is constant initially (at moderate concentrations), however falls at higher trap concentrations. On extraction of vertical electric field near drain edge for a drain bias lower than breakdown voltage, as shown in Fig. 4.3(c), an increase in the peak electric field near drain edge with acceptor trap concentration can be clearly seen. As the peak field near drain edge increases, breakdown voltage falls with increase in acceptor trap concentration.

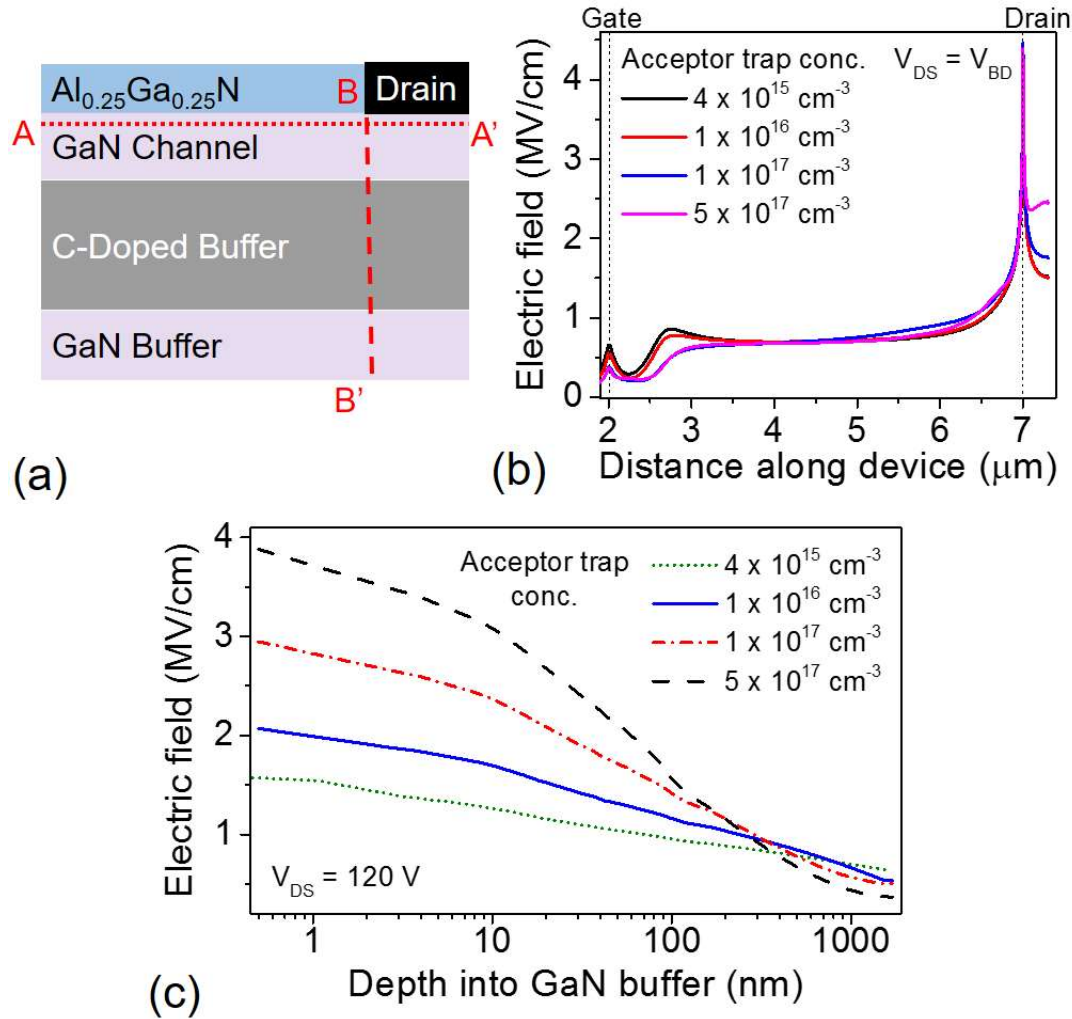


Figure 4.3: (a) Device structure depicting cut lines along which lateral electric field (A - A') and vertical electric field (B - B') are extracted. (b) Lateral electric field extracted at the onset of avalanche breakdown for different acceptor trap concentrations. Avalanche hot spot near the drain edge can be observed in all the cases. (c) Vertical electric field extracted for different acceptor trap concentrations indicating dependence of vertical field on acceptor trap concentration.

In order to further explain the dependence of vertical field on acceptor traps (Fig. 4.3(c)) and field peaking near drain edge, it is important to consider its impact on buffer properties. Apart from affecting the buffer resistivity, acceptor traps in GaN buffer can (i) introduce free holes in GaN buffer, as depicted in Fig. 4.4(a), and (ii) act as charged ions upon ionization, as depicted in Fig. 4.4(b) and Fig. 4.4(c). In Fig. 4.4(b) and Fig. 4.4(c), ionized acceptor trap density represents negative charge due to trapping of an electron. These two factors can change the space charge distribution across the GaN buffer and hence can potentially readjust the electric field. In order to understand the former point, free hole density in GaN buffer is extracted for different acceptor trap concentrations, as shown in Fig. 4.4(a). It clearly indicates that increasing acceptor trap concentration induces free hole density in GaN buffer, which makes it marginally p-type.

This results in a reduced buffer resistivity and hence reduced breakdown voltage due to increased buffer leakage. The trap induced hole density was found to be orders of magnitude lower than the acceptor trap concentration, which is attributed to the fact that these traps are located deep in the energy gap (0.9 eV away from the valence band edge) and therefore from Fermi-Dirac statistics can induce a limited number of holes.

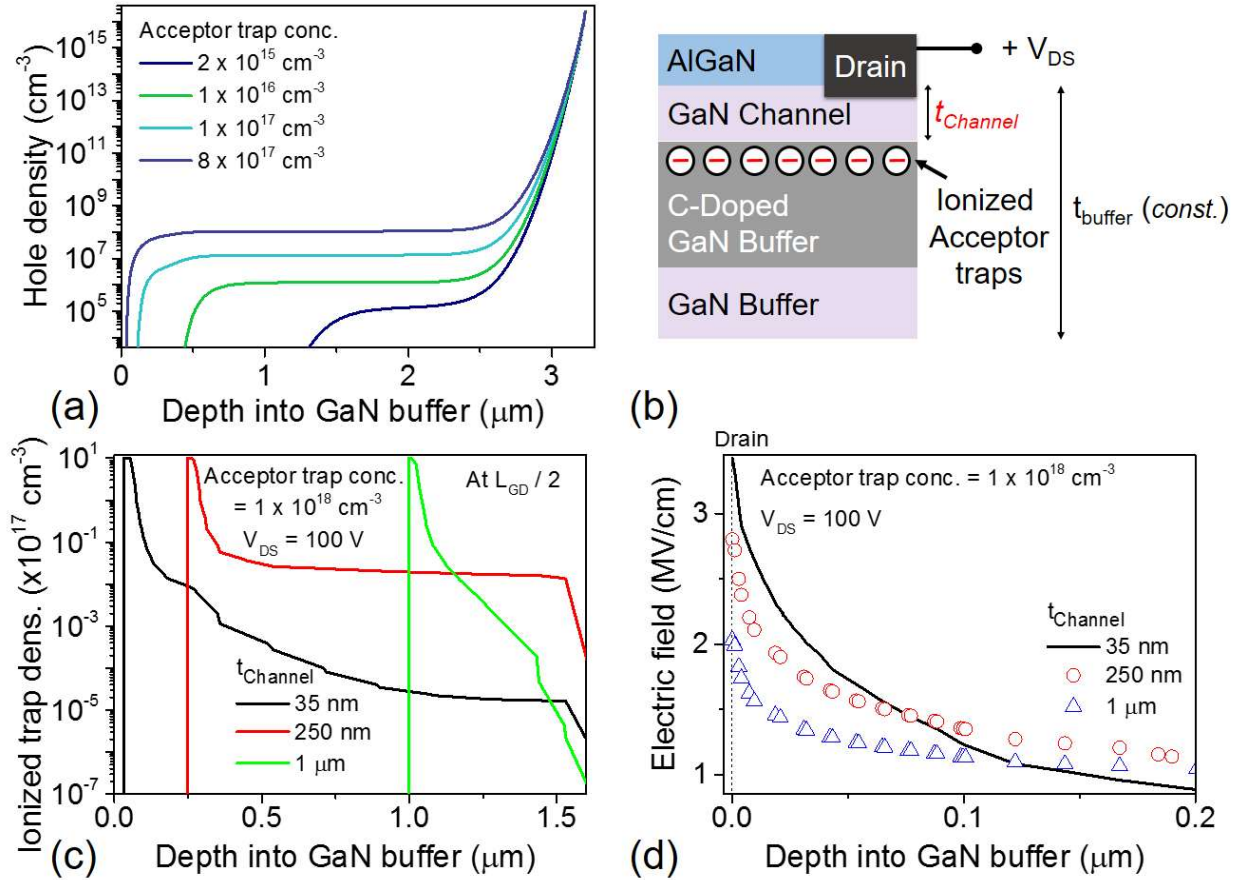


Figure 4.4: (a) Impact of C-Doping induced acceptor traps on parasitic hole density in GaN buffer. (b) Device structure depicting the variable t_{Channel} used for analyzing the vertical field between positively biased drain electrode and negatively charged ionized acceptor traps. (c) Ionized acceptor trap profile along a vertical cut line located at a distance of $L_{\text{GD}}/2$ from gate edge and extracted for different values of t_{Channel} . (d) vertical electric field, extracted along a vertical cut line near drain edge for different values of t_{Channel} , indicating a dependence of electric field peak near drain edge on the channel thickness.

In order to understand the later point, i.e. impact of charged ions on vertical field, t_{Channel} as shown in Fig. 4.4(b) was increased, to shift the ionized charges away from the channel, while keeping all other parameters constant. However, while increasing t_{Channel} , $t_{\text{C-Doped}}$ was reduced so as to keep the total buffer thickness unchanged. With this variation, effectively the distance between positively biased drain electrode and acceptor trap affected region is increased while maintaining all other parameters constant. This is depicted in Fig. 4.4(c). Resulting electric field in the channel region, as shown in Fig. 4.4(d), shows a reduction in electric field near drain edge as channel thickness is increased. This further quantifies the dependence of electric field on acceptor traps in the buffer region which can now be explained as follows. As acceptor traps ionize by capturing electrons from 2DEG, they build a negative charge in the buffer region. Since these traps are present beneath the drain electrode as well, an electric field exists between the positively biased drain electrode and negatively charged acceptor ions. The peak of this electric field increases as the distance between drain electrode and trap affected region is reduced (see

4.4(d)) or if acceptor trap concentration is increased (see Fig. 4.3(c)). This effect combined with electric field crowding near the drain edge results in reduced breakdown voltage of the device at higher acceptor trap concentrations even when the leakage current continues to fall.

Limited by the parasitic hole density and adverse impact on vertical electric field, computations suggest breakdown voltage to saturate at ~ 200 V for an $L_{GD} = 5 \mu\text{m}$ and $t_{C\text{-Doped}} = 1.5 \mu\text{m}$, while considering C-Doping to behave as acceptor traps. However, these values are much smaller than the experimentally observed breakdown voltage of ~ 900 V for a C-Doping concentration of $\sim 4 \times 10^{19} \text{ cm}^{-3}$ and similar device dimensions [Bahat-Treidel *et al.* 2010]. This suggests that C behaving only as acceptor traps in GaN buffer cannot completely explain the improvement in breakdown voltage observed experimentally in earlier works [Bahat-Treidel *et al.* 2010].

4.3.2 Possibility 2: C-Doping as Self-Compensating Acceptor and Donor Traps

As C behaving as acceptor traps alone is not able to explain improvement in breakdown voltage, observed experimentally, C-Doping is modeled in self-compensating configuration i.e. as deep acceptor trap with energy $E_V + 0.9 \text{ eV}$ [Lyons *et al.* 2010] and self-compensating donor traps with energy $E_C - 0.11 \text{ eV}$ [Uren *et al.* 2012, Verzellesi *et al.* 2014a, Uren *et al.* 2015]. Figure 4.5(a) indicates an improvement in breakdown voltage as donor traps are introduced in the C-Doped region for a fixed acceptor trap concentration. However, this improvement is limited by acceptor trap concentration present in the C-Doped region, with a reduction in breakdown voltage observed as donor trap concentration approaches acceptor trap concentration. As can be seen from Fig. 4.5(b), this reduction in breakdown voltage is accompanied by an increased buffer leakage current, suggesting formation of a parasitic leakage path/channel. Fig. 4.6(a) depicts a further improvement in breakdown voltage with increase in gate to drain spacing as the donor trap concentration is increased.

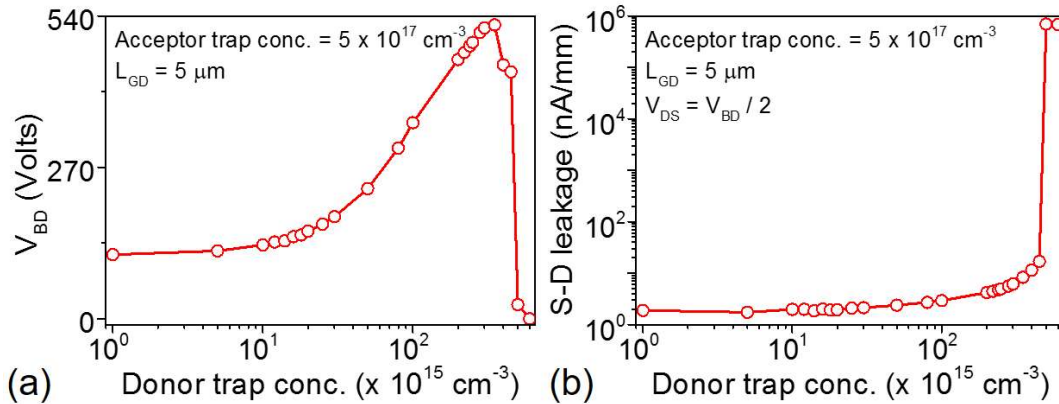


Figure 4.5: Impact of donor trap concentration on (a) breakdown voltage (V_{BD}) of the device, and (b) leakage current through the device extracted at $V_{DS} = V_{BD} / 2$. Thickness of C-doped region, $t_{C\text{-doped}} = 1.5 \mu\text{m}$.

In Fig. 4.6, a relatively higher acceptor trap concentration was used compared to what was used in Fig. 4.5 to analyze breakdown voltage up to higher donor trap concentration without affecting the leakage current. Similar improvement in breakdown voltage with L_{GD} is also observed experimentally in earlier works when C-Doping concentration was increased [Bahat-Treidel *et al.* 2010].

Furthermore, increasing the acceptor trap concentration while having a constant donor trap concentration, as shown in Fig. 4.6(b), also results in an improved breakdown voltage. An agreement with experimental data, as shown in Fig. 4.1(b), was found for acceptor trap concentration of $\sim 3 \times 10^{18} \text{ cm}^{-3}$ along with a compensating donor trap concentration of $\sim 5 \times 10^{17}$

cm^{-3} , justifying the use of higher trap concentrations in Fig. 4.6. From Fig. 4.6(a) and Fig. 4.6(b), it can be fairly concluded that the relative concentration of acceptor and donor traps controls the avalanche breakdown in these devices with donor traps having a more pronounced impact on breakdown voltage, however it must stay below the acceptor trap concentration. Physics behind this breakdown voltage improvement with traps in self-compensating configuration is discussed in following sections.

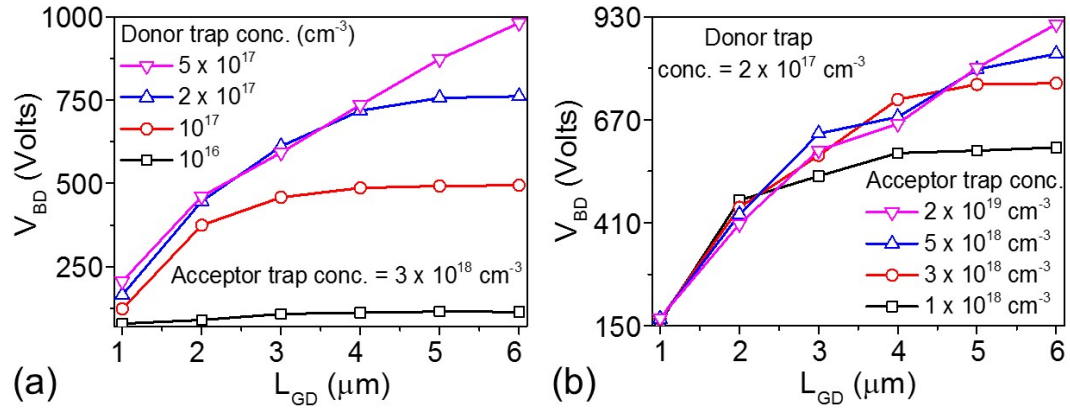


Figure 4.6: (a) Impact of donor trap concentration on breakdown voltage as a function of gate to drain spacing, in presence of acceptor traps induced by C-Doping. (b) Impact of increasing acceptor trap concentration in presence of a fixed donor trap concentration on breakdown voltage as a function of L_{GD} . Thickness of C-doped region, $t_{\text{C-Doped}} = 1.5 \mu\text{m}$.

4.4 IMPACT OF TRAPS ON AVALANCHE BREAKDOWN: PHYSICAL INSIGHT

As presented in the previous section, the buffer traps are expected to affect vertical electric field. Hence, the device considered in this section has higher L_{GD} of $10 \mu\text{m}$ and L_{FP} of $3 \mu\text{m}$ with a thicker C-doped buffer of $3 \mu\text{m}$. This is done to isolate impact of lateral electric field and to have a better understanding of the impact of traps on vertical electric field and avalanche breakdown.

4.4.1 Donor traps: Impact on free charge carriers & vertical electric field in GaN buffer

The impact of donor traps in presence of acceptor traps in GaN buffer can be considered to be composed of following three effects: (i) it can compensate free holes which either are introduced by acceptor traps or e-h pair production due to impact ionization, (ii) change in space charge distribution and therefore field re-adjustment due to introduction of free electrons in the buffer, and (iii) introduction of ionized traps (fixed charge) in presence of acceptor traps in the buffer, thereby affecting vertical electric field due to change in space charge distribution.

The first aspect that donor traps can compensate free holes is depicted in Fig. 4.7(a). It can be clearly observed that introducing donor traps can compensate free holes introduced by acceptor traps already present in GaN buffer. The same is expected for holes produced by onset of impact ionization process, which can potentially delay the impact ionization process. Furthermore, as shown in Fig. 4.7(b), higher donor trap concentration results in an increased ionized acceptor trap density. Thus, the free electrons induced by donor traps in GaN buffer are trapped in the acceptor traps and hence no free electrons are introduced in GaN buffer. This ensures that the introduced donor traps don't contribute in buffer leakage. However, this holds true only if donor trap concentration is lower than the acceptor trap concentration. As the concentration of donor traps approaches that of acceptor traps, a significant concentration of free electrons will be introduced in the GaN buffer, resulting in an increased leakage (Fig. 4.5(b)). This also explains the reduction in breakdown voltage observed at higher donor trap concentrations in Fig. 4.5(a).

In order to evaluate the third aspect, i.e., impact of donor traps on vertical electric field, electric field contours at the onset of avalanche breakdown for different donor trap concentrations are compared in Fig. 4.7(c) and Fig. 4.7(d). It depicts a higher electric field in the deep GaN buffer region for devices with higher donor trap concentration. Further, the electric field extracted along a cut-line near the drain edge, as shown in Fig. 4.8(a), indicates an increased redistribution of electric field throughout the GaN buffer as donor trap concentration is increased, which relaxes the electric field peak near the drain edge and increases device's voltage handling capacity. It should be noted that the peak electric field value near the drain electrode remains fixed for all the cases while the absolute drain voltage (=breakdown voltage) consistently increases with donor trap concentration. This is attributed to the fact that the electric field profiles are extracted at the onset of avalanche breakdown and given that avalanche hot spot is located at the same point, approximately a fixed peak value (= critical field for impact ionization) is observed. It should however be noted that while peak field was pinned to critical breakdown field, drain voltage for the same (=breakdown voltage) increases as the e-field is redistributed in the deep GaN buffer region. The physics behind vertical field redistribution with donor traps is explained below.

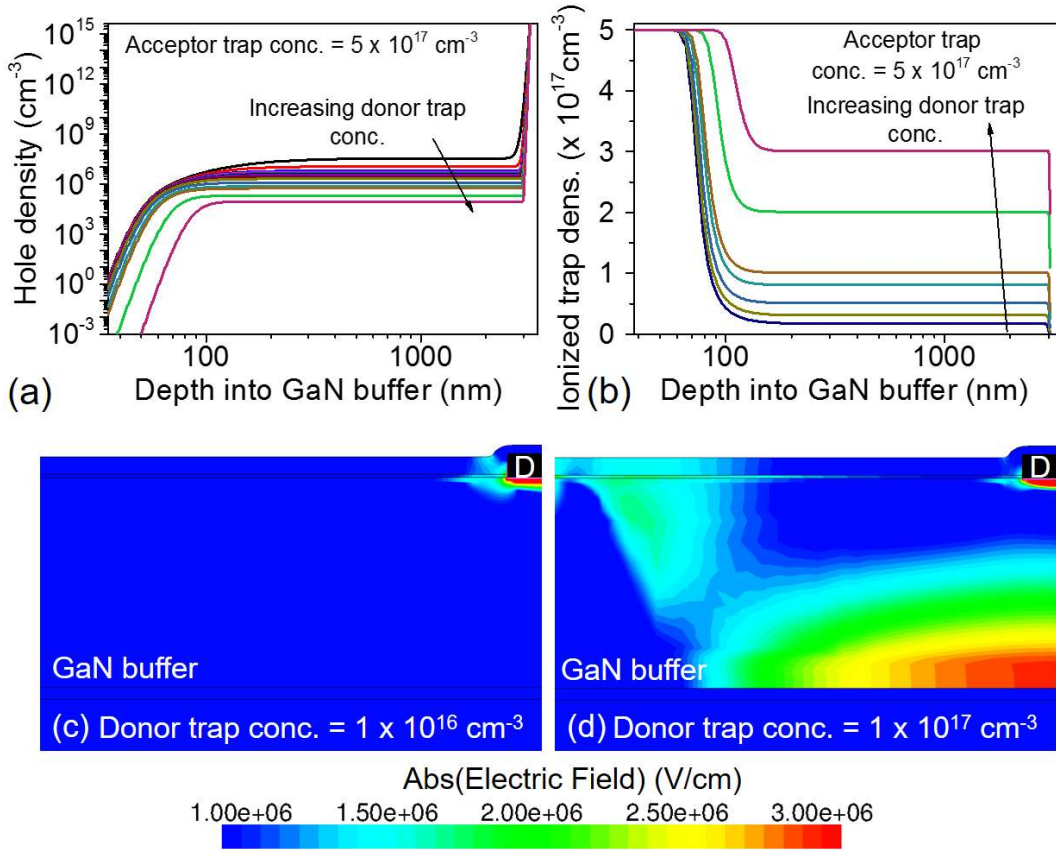


Figure 4.7: (a) Reduction in parasitic hole density on compensation by donor traps in the C-Doped region, (b) Increase in ionized acceptor trap density in C-Doped region on increasing the donor trap concentration. Electric field contours extracted at the onset of avalanche breakdown with a constant acceptor trap concentration of $5 \times 10^{17} \text{ cm}^{-3}$ and a donor trap concentration of (c) $1 \times 10^{16} \text{ cm}^{-3}$, and (d) $1 \times 10^{17} \text{ cm}^{-3}$. A significant field redistribution inside GaN buffer can be observed as donor trap concentration is increased.

As with increase in donor trap concentration a significant difference is observed in the electric field in deep GaN buffer region, computations were done with increased channel thickness (t_{channel} in Fig. 4.1(a)) to investigate impact of donor traps on electric field. Vertical electric field near the drain edge extracted for a channel thickness of $1 \mu\text{m}$ is shown in Fig. 4.8(b). A similar impact on vertical field can be observed with increase in donor trap concentration, which is now limited to the lower buffer region where donor traps were considered.

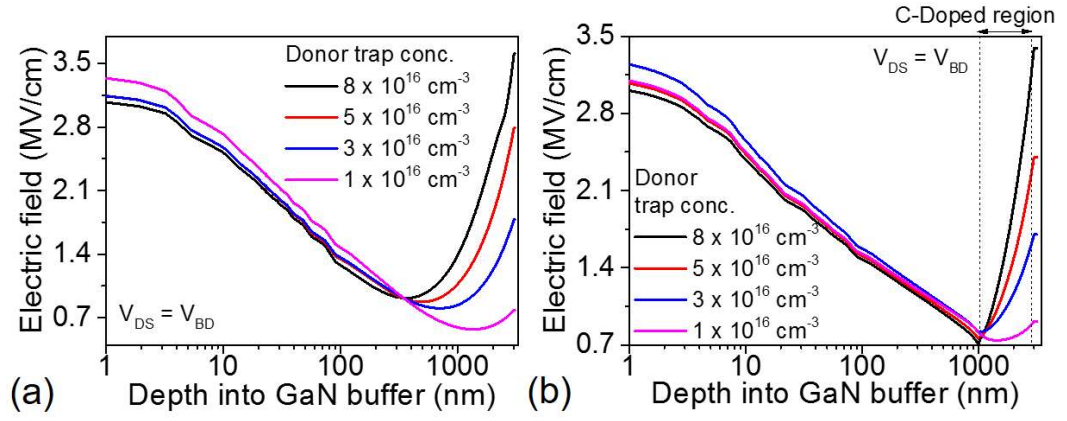


Figure 4.8: (a) Redistribution of vertical electric field in the deep GaN buffer observed with increasing donor trap concentration. The electric field is extracted along a cutline through the GaN buffer taken near drain electrode. (b) Similar redistribution of vertical electric field is observed on increasing channel thickness, t_{channel} , to $1 \mu\text{m}$. Acceptor trap concentration for these observations was kept constant at $5 \times 10^{17} \text{ cm}^{-3}$.

This further indicates that donor traps primarily affect the electric field in deep GaN buffer region. In order to explain this behavior, further analysis was carried out with this increased channel thickness ($1 \mu\text{m}$). Figure 4.9(a) compares vertical electric field for two different donor trap concentrations extracted at similar drain voltage. It can be clearly observed that increasing donor trap concentration relaxes electric field near the drain edge by redistributing it in the buffer region. Further, impact on electric field due to increasing drain voltage is shown in Fig. 4.9(b). It indicates that at lower drain voltages, electric field is confined in a narrow region near drain edge. However, at higher drain voltages, a significant redistribution of the field in deep GaN region is observed restricting the electric field peak near drain edge to lower values. This dynamic behavior of electric field re-distribution together with behavior of traps can be explained by considering their impact on space charge profile. As acceptor traps ionize by accepting an electron, they behave as negatively charged ions, whereas donor traps become positively charged by donating their electron/capturing a hole. In ionized state, these traps will thus modify the space charge profile and hence the electric field. This is validated using vertical electric field in the GaN buffer region along with a comparison of the ionized donor and acceptor trap densities at $V_{DS} = 200 \text{ V}$ and $V_{DS} = 300 \text{ V}$ as shown in Fig. 4.10(a) and 4.10(b), respectively.

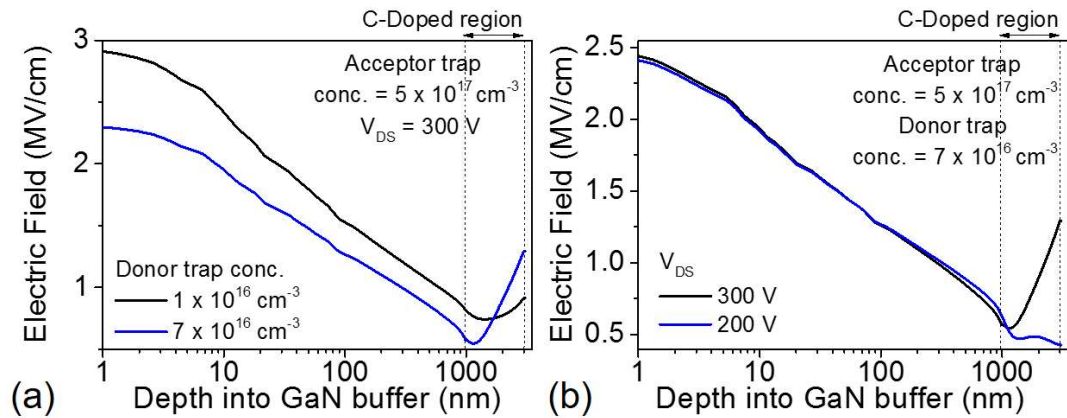


Figure 4.9: Vertical electric field near the drain edge, (a) extracted for different donor trap concentrations at $V_{DS} = 300 \text{ V}$, and (b) extracted at different drain bias voltages for a donor trap concentration of $7 \times 10^{16} \text{ cm}^{-3}$.

As shown in Fig. 4.10(a), at lower drain bias voltages, positive charge by ionized donor traps is balanced by approximately equal negative charge due to ionized acceptor traps. This results in a nearly constant electric field in this region as $\frac{dE}{dx} \approx \frac{qN_{IDT}}{\epsilon_{GaN}} - \frac{qN_{IAT}}{\epsilon_{GaN}} \approx 0$, where N_{IDT} = ionized donor trap concentration, N_{IAT} = ionized acceptor trap concentration, and ϵ_{GaN} is electric permittivity of GaN. On the other hand, as shown in Fig. 4.10(b), with an increase in drain bias, ionized acceptor trap concentration reduces on account of de-trapping and movement of electrons under influence of drain electric field. On similar grounds, the ionized donor trap concentration remains constant as it is ionized by donating electrons. As a result, a net positive charge is present in this region due to dominating ionized donor trap concentration. This modifies space charge profile which enables vertical electric field to redistribute between two electric field peaks, one near drain edge and another at the lower edge of donor trap affected region (see Fig. 4.10(b)). Further, an increase in donor trap concentration increases the net positive charge in this region, leading to an increased field redistribution in the deep GaN buffer (see Fig. 4.8(b)), as $\frac{dE}{dx} \approx \frac{q(N_{IDT} - N_{IAT})}{\epsilon_{GaN}}$. This leads to an improved breakdown voltage with an increase in donor trap concentration.

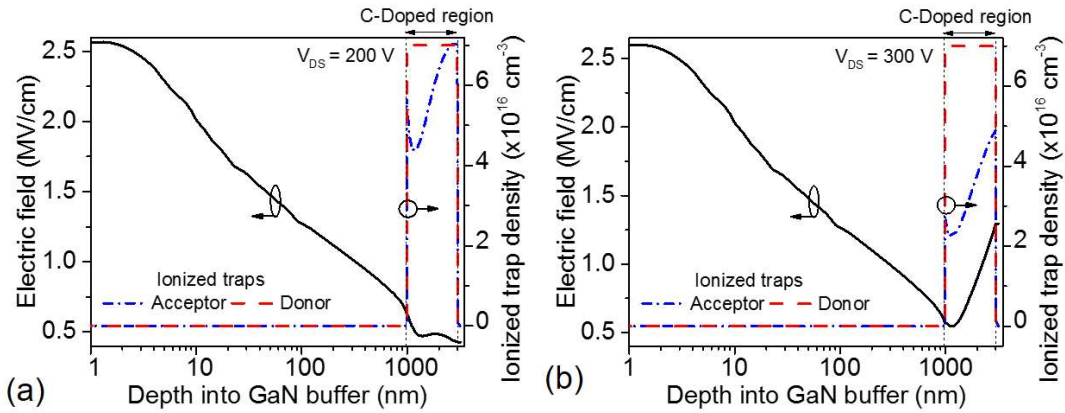


Figure 4.10: Vertical electric field along with ionized donor and acceptor trap densities extracted near the drain edge at a V_{DS} of (a) 200 V, and (b) 300 V. A clear dependence of electric field on ionized trap densities can be observed.

4.4.2 Acceptor traps: Impact on avalanche generation

A comparison of vertical electric field near drain edge at different acceptor trap concentrations for $t_{\text{Channel}} = 1 \mu\text{m}$, as shown in Fig. 4.11(a), indicates vertical electric field to be independent of acceptor trap concentration. However, Fig. 4.6(b) suggests an improvement in breakdown voltage as acceptor trap concentration is increased, for a reduced t_{Channel} of 35 nm. This suggests the acceptor traps to be involved in mechanism other than electric field redistribution in the deep GaN buffer region which however assists in breakdown voltage improvement. To understand impact of acceptor traps on breakdown voltage, electron capture cross section ($A_{\text{exSection}}$) for these traps was taken as a parameter and device with a reduced t_{Channel} of 35 nm was considered. Fig. 4.11(b) compares breakdown characteristics of device for two different $A_{\text{exSection}}$ values. A reduction in breakdown voltage from ~ 1190 V to 700 V can be observed with a reduction in $A_{\text{exSection}}$ from $8 \times 10^{-16} \text{ cm}^2$ to $5 \times 10^{-16} \text{ cm}^2$. Further, the IV characteristics interestingly indicate an increase in current at approximately similar voltage (~ 700 V) for both the cases. However, for computations with higher $A_{\text{exSection}}$, this increase in drain current was suppressed until reaching a hard breakdown at higher V_{BD} values of ~ 1190 V. This suggests capturing of electrons in acceptor traps to assist in suppressing avalanche generation phenomena thereby increasing the breakdown voltage. To have a further insight into this effect, computations were done with $A_{\text{exSection}}$ of $8 \times 10^{-16} \text{ cm}^2$ and impact of avalanche generation was evaluated by comparing computations with and without accounting for impact ionization.

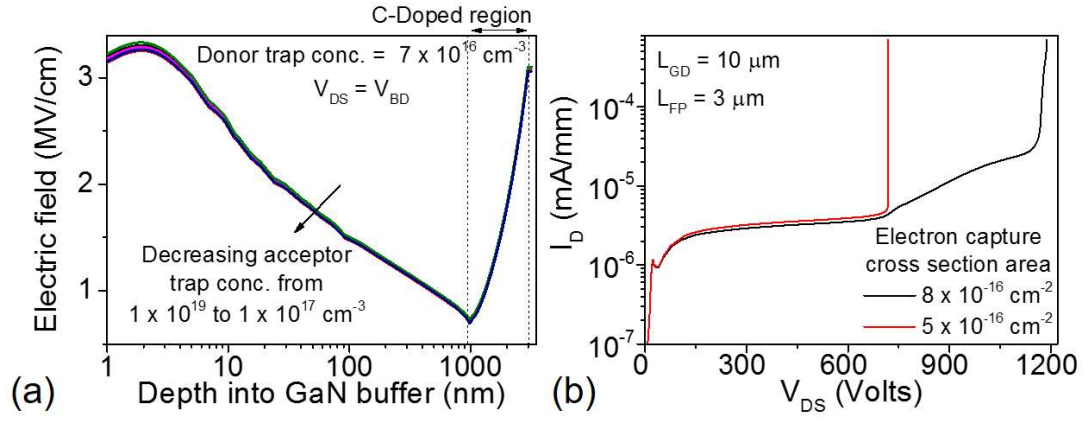


Figure 4.11: (a) Impact of increasing acceptor trap concentration on vertical electric field profile near the drain edge. Electric field redistribution in GaN buffer is found to be independent of acceptor trap concentration. (b) Off state breakdown characteristics of device with carbon doping modeled as compensating traps and with different electron capture cross section area for acceptor traps. Acceptor trap concentration of $5 \times 10^{17} \text{ cm}^{-3}$ and donor trap concentration of $2 \times 10^{17} \text{ cm}^{-3}$ were considered.

A comparison of electric field and ionized acceptor trap density at $V_{BD} = 700 \text{ V}$ for the two cases, as shown in Fig. 4.12(a), indicates a similar profile. This is also expected as electric field at this bias voltage is lower than the critical field value and hence avalanche generation is minimum. However, as the drain bias is increased to $V_{BD} = 900 \text{ V}$, as shown in Fig. 4.12(b), a significant difference in electric field can be observed for the two cases as electric field in deep GaN buffer crosses the critical field value of $\sim 3 \times 10^6 \text{ V/cm}$. Further, ionized trap density for the two cases, as shown in Fig. 4.12(b), indicates a significant increase in ionized trap concentration when impact ionization was considered. This can be explained as follows. Electrons generated during impact ionization in the deep GaN buffer region drift under the influence of drain electric field and is subsequently captured by acceptor traps present in the GaN buffer. This capturing of electrons slows down the avalanche process. In addition to this, capturing of electrons ionizes the acceptor traps and modifies the space charge profile. This is reflected in electric field as well, as shown in Fig. 4.12(b), which shows a reduced field in the deep GaN region thereby further suppressing the avalanche generation. This results in an improvement in breakdown voltage as acceptor trap concentration is increased. It should be noted that practically the trap profile will be different from that considered in these sections and will depend on the activation energies associated with C forming acceptor/donor trap sites. However, similar physics will be applicable in those scenarios as well.

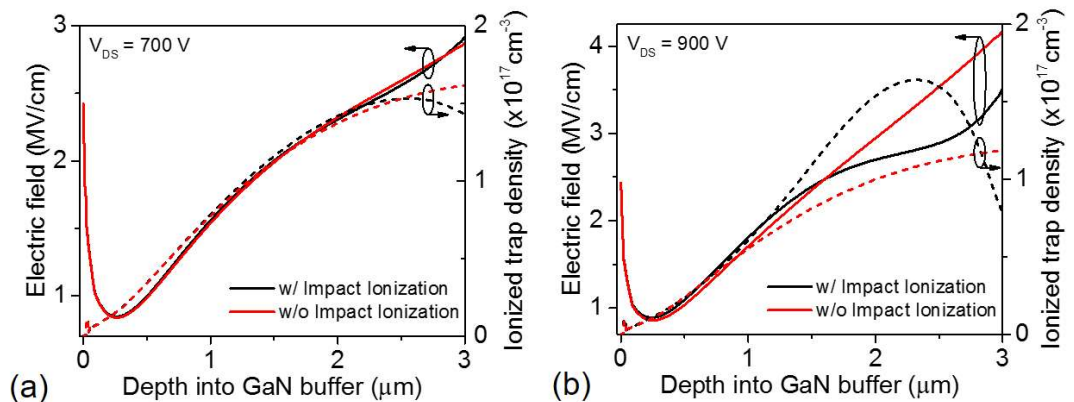


Figure 4.12: Electric field and ionized trap density comparison for device when impact ionization was considered and without it, extracted at a drain bias of (a) 700 V and (b) 900 V. Acceptor trap concentration of $5 \times 10^{17} \text{ cm}^{-3}$ and donor trap concentration of $2 \times 10^{17} \text{ cm}^{-3}$ were considered.

4.4.3 Combined impact of acceptor and donor traps

Acceptor traps effectively control avalanche generation by capturing electrons and are responsible for associated field shaping. A similar effect is expected for avalanche generated holes and donor traps. However, donor traps being shallow in nature were found to be completely ionized by either acceptor traps or movement of electrons under drain electric field, thereby limiting the sites available for capturing holes. Thus, donor traps primarily contribute in electric field redistribution and no such variation with hole capture cross section was observed. Further, as discussed earlier, the peak donor trap concentration that can result in breakdown voltage improvement is limited by acceptor traps present in the buffer. With these observations it can be fairly concluded that presence of C in self-compensating configuration with dominating acceptor traps is responsible for breakdown voltage improvement in AlGaIn/GaN HEMT devices.

4.5 DESIGN PARAMETERS FOR C-DOPED GAN BUFFER

Successful modeling of behavior of C-Doping makes it possible to discuss GaN buffer designing with respect to C-Doping related parameters. This section discusses the design parameters related to C doped GaN buffer designing.

4.5.1 Channel thickness

Figure 4.13(a) shows the impact of t_{Channel} on breakdown voltage of the device. In these computations, total buffer thickness is kept constant. Thus, with an increase/decrease in the t_{Channel} , thickness of the C-Doped region is adjusted in order to keep the total buffer thickness constant at 1.785 μm .

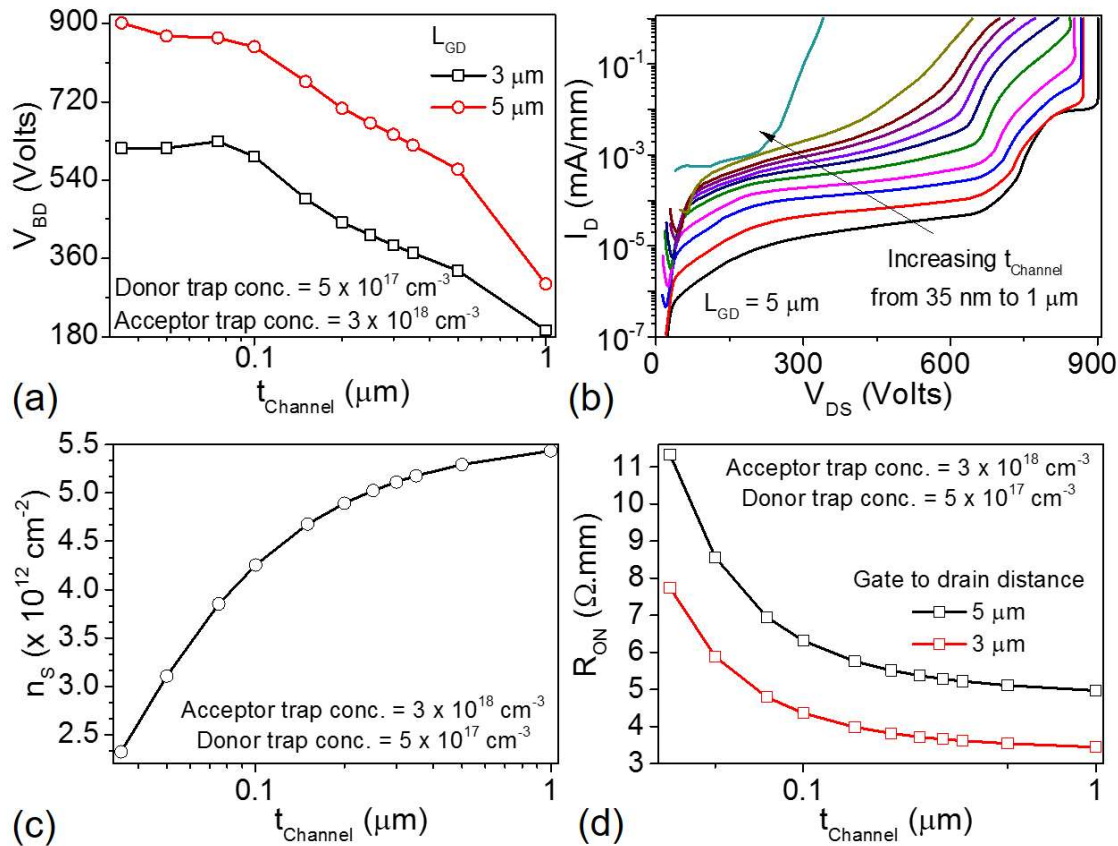


Figure 4.13: (a) Impact of GaN channel thickness on the breakdown voltage of the device. (b) Corresponding I-V characteristics of the device with increasing GaN channel thickness. Total buffer thickness was kept constant at 1.785 μm for all the computations. Impact of undoped channel thickness on (c) sheet charge density, and (d) ON-resistance of the device. An optimum channel thickness is obtained when DC performance is maximized without significantly compromising on the breakdown performance.

In case of leaky devices, the drain voltage at which drain current exceeded 1 mA/mm was considered as breakdown voltage. It can be observed from Fig. 4.13(b) that with increasing t_{Channel} , leakage through the GaN channel increases. However, it does not significantly affect the hard breakdown or onset of avalanche effect. This further quantifies the observation that C-Doping is responsible for E-field redistribution in the deep GaN buffer regions besides controlling buffer resistivity. This leads to a negligible impact on breakdown voltage up to certain channel thickness (see Fig. 4.13(a)). However, shifting the C-Doped region deeper into the GaN buffer increases the leakage through the GaN channel which results in significant lowering of breakdown voltage. At sufficiently thicker GaN channel ($\sim 1 \mu\text{m}$), the breakdown path was formed in the GaN channel with hard breakdown taking place at significantly lower values of drain voltage (see Fig. 4.13(b)). Figures 4.13(c) and 4.13(d) suggest a significant improvement in sheet charge density (n_s) and ON-resistance (R_{ON}) of the device as channel thickness is increased, which is attributed to shift of acceptor traps away from the channel and associated reduction in electron capture by these traps. Interestingly, this improvement is restricted up to a certain thickness ($\sim 250 \text{ nm}$) beyond which it saturates. Fig. 4.13(c) and Fig. 4.13(d) indicate presence of an optimum channel thickness ($\sim 125 \text{ nm}$) where the DC performance of the device can be maximized while maintaining the breakdown performance.

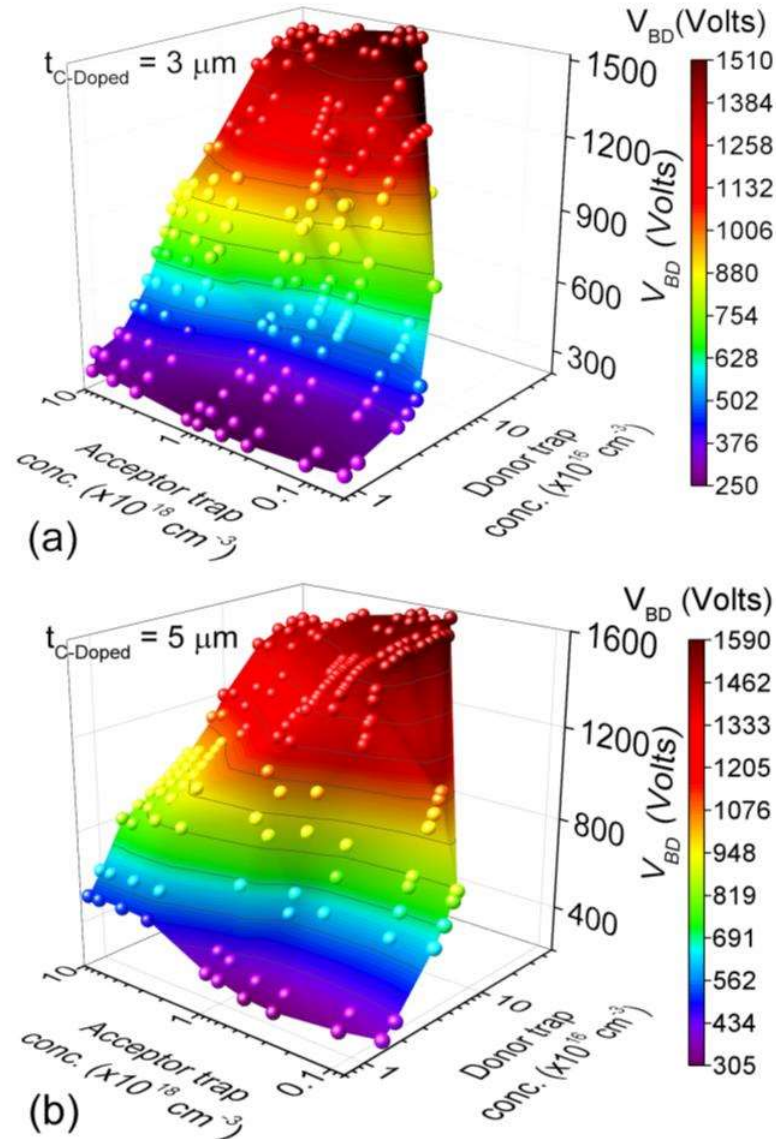


Figure 4.14: Impact of relative acceptor and donor trap concentrations induced by C-Doping in GaN buffer on breakdown voltage of the device for a C-Doped region thickness of (a) $3 \mu\text{m}$, and (b) $5 \mu\text{m}$. A channel thickness of 35 nm was used.

4.5.2 C-Doping: Optimizing relative trap concentration

From the above discussions it is clear that presence of acceptor and donor traps in the GaN buffer affects the breakdown voltage. Moreover, the upper limit on donor trap concentration is decided by the acceptor trap concentration and leakage through GaN buffer. This section presents impact of relative donor/acceptor trap concentrations on different device figure of merit parameters viz. breakdown voltage, leakage current, sheet charge density and ON-resistance. The lateral device dimensions are kept constant at $L_{GD} = 10 \mu\text{m}$, and $L_{FP} = 3 \mu\text{m}$ to isolate the effect of lateral electric fields. Further, the channel thickness is kept constant at 35 nm. From Fig. 4.14(a) and Fig. 4.14(b), it can be observed that irrespective of thickness of C-Doped region, breakdown voltage improves with donor trap concentration. Further, improvement with acceptor trap concentration ceases at much lower values. This is as expected as donor traps contribute to the vertical field redistribution and are primarily responsible for breakdown voltage improvement. This further emphasizes the importance of relative concentration of acceptor and donor traps induced by C-Doping. The leakage current depicted in Fig. 4.15 highlights a window of acceptor trap concentration where the leakage is minimum for complete range of donor trap concentration. Thus, with a moderate acceptor trap concentration, donor trap concentration can be maximized to achieve optimum breakdown voltage with low leakage current.

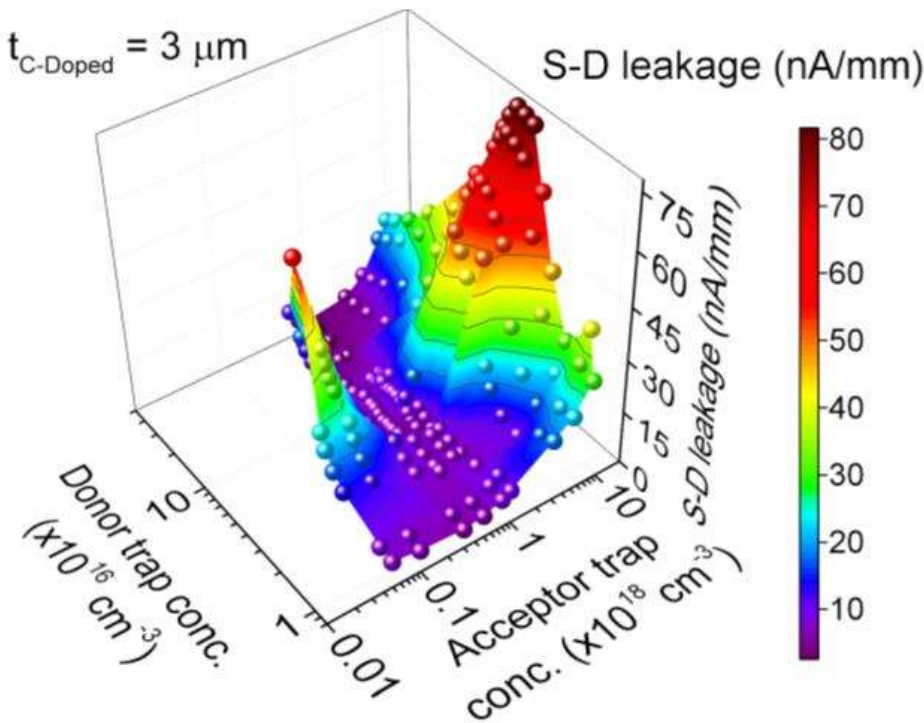


Figure 4.15: Impact of C-Doping induced trap concentration on S-D leakage current extracted at $V_{DS} = V_{BD} / 2$.

Further, the sheet charge density and ON-resistance, as shown in Fig. 4.16(a) and Fig. 4.16(b), respectively, show dependence on acceptor trap concentration and a weaker dependence on donor trap concentration. This is attributed to the fact that the acceptor traps can capture channel electrons and hence reduce n_s , whereas donor traps do not affect the channel electron density.

A comparative analysis of all the performance parameters suggests a moderate acceptor trap concentration ($\sim 1 \times 10^{18} \text{ cm}^{-3}$) with optimized donor trap concentration ($\sim 2 \times 10^{17} \text{ cm}^{-3}$) to maximize the breakdown voltage while maintaining low leakage and acceptable ON-resistance. Behavior of C as donor or acceptor is dependent on process conditions as suggested in [Lyons *et*

al. 2014] and hence an optimization of process conditions can result in the required profile. It should be noted that these trap concentrations are taken without considering any dislocations/defects induced traps introduced during the epitaxial growth.

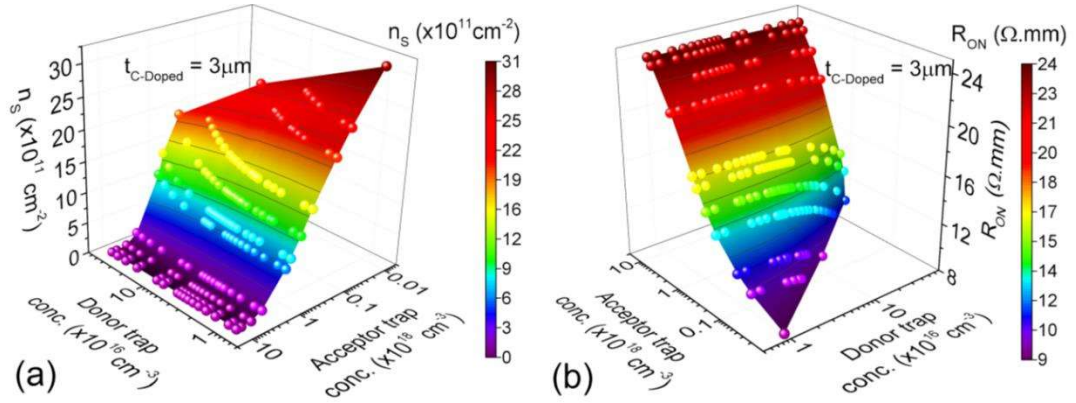


Figure 4.16: Impact of C-Doping induced trap concentration on (a) sheet charge density, and (b) ON-resistance of the device. Channel thickness was kept constant at 35 nm.

4.5 CONCLUSION

Carbon doping modeled as only acceptor traps was found to have a limited impact on breakdown voltage of the device. Self-compensating nature of traps introduced by C-Doping in GaN was found to be the key parameter controlling breakdown voltage in these devices. We established that the donor traps induced by C-Doping are important in deciding the breakdown voltage of the device. However, its concentration is required to be lower than that of acceptor traps for buffer to remain resistive, thereby highlighting the importance of self-compensating nature of traps induced by C in GaN buffer. Space charge modulation by donor traps was found to be the primary reason behind vertical electric field redistribution improving the breakdown voltage. On the other hand, acceptor traps introduced by C-Doping were found to capture the electrons generated by avalanche phenomena, thereby delaying the avalanche breakdown as well as shaping the electric field in deep GaN buffer. An analysis of design parameters related to buffer designing with C-doping modeled as self-compensating traps suggests an optimum channel thickness which results in a lower ON-resistance while maintaining the breakdown voltage.

Further, TCAD computations suggest a moderate acceptor trap concentration combined with an optimized donor trap concentration to be primary design factor for optimizing breakdown performance, leakage current and ON-resistance of the device.

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