Investigation of Defect Characteristics and Carrier Transport Mechanisms in GaN Layers With Different Carbon Doping Concentration

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Abstract—In this article, a metal/carbon-doped GaN (GaN:C)/Si-doped GaN (GaN:Si) structure was used to investigate the defect characteristics and carrier transport mechanisms in GaN:C layers with different carbon doping concentration. Capacitance-voltage, current-voltage, and deep-level transient spectroscopy measurements were performed at different temperatures. At forward bias, a pinning effect was found at the interface of the GaN:C/GaN:Si layer, due to the defects capturing electrons. The forward currents of the samples with high carbon doping concentration ($N_C > 1 \times 10^{19} \text{ cm}^{-3}$) increase gradually with increasing forward bias voltage. Ohm's law, space-charge-limited current, and variable-range-hopping mechanisms may dominate the forward current. For the samples with low carbon doping concentration ($N_C < 1 \times 10^{19} \text{ cm}^{-3}$), a device turning on behavior was observed, which is attributed to the carriers overcoming a potential barrier. In addition, the DLTS spectra reveal that only electron trapping happens at forward bias for the samples with high carbon doping concentration, while, in addition, hole trapping was observed for the samples with low carbon doping concentration. The process of the carrier capture by defects was demonstrated.

Index Terms—Carbon doping, defects, GaN buffer, transport mechanism.

I. INTRODUCTION

RECENTLY, GaN-on-Si has become one of the most promising candidates for high-power and high-frequency applications [1]–[3]. Thanks to the epitaxy on 8-in large-diameter Si substrates, the cost can be significantly reduced [4], [5]. However, the mismatch of lattice and thermal expansion between Si and GaN requires a strain management layer [transition layer (TL)] to control the wafer warp. Above the TL, a GaN buffer layer is grown, which is significant for high-power and RF devices due to its impact on the vertical leakage, the breakdown behavior, and the current collapse (CC). Carbon doping is usually employed to achieve a high resistivity GaN buffer layer, which, reportedly, can compensate the initial n-type background doping of GaN, resulting in a semi-insulating layer [6], [7]. However, the carbon doping also induces defects to the GaN layer, which may capture electrons under OFF-state switching and degrade the ON-state resistance. Therefore, it is significant to adopt a proper carbon doping concentration to control the leakage current and avoid the CC. Some characterization techniques, such as photoluminescence [8]–[10], deep-level transient spectroscopy (DLTS) [11], and back-gate stressing [12], were employed to detect the defects located at different energy levels induced by the carbon doping. However, the impact of the carbon doping concentration on the defects and carrier transport mechanism still lacks detailed investigation. Different carrier transport mechanisms, including space-charge-limited current (SCLC) [13]–[15], hopping [16], [17], and Poole–Frenkel (PF) emission [18], [19], were proposed by various groups to interpret charge conduction in GaN:C. However, the traditional high-electron-mobility transistor (HEMT) structure makes it difficult to separate the channel and TLs' influence on the GaN:C buffer layer, hindering the full understanding of the physics model of the GaN:C buffer layers.

Recently, Koller *et al.* [20] demonstrated a simple structure to gain more insight into this GaN:C layer, which can

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Fig. 1. Cross-sectional schematic of the devices fabricated on the four samples.

eliminate the influence of the channel layers. Here, we used a similar structure and fabricated Metal/GaN:C/GaN:Si devices to analyze the defect characteristics and carrier transport mechanisms of the GaN:C layer. Four samples with a GaN layer doped with different carbon concentrations were fabricated. C - V , I - V , and DLTS measurements were performed. Significantly different defect characteristics and carrier transport mechanisms between GaN:C layers with low and high carbon concentration doped were found. Furthermore, the band diagram of the samples under forward bias was derived, explaining the defect charging process and carrier transport behavior of the structure.

II. MATERIAL GROWTH AND DEVICE FABRICATION

In this work, 4 wafers were epitaxially grown on 6-in p-type Si (111) substrates with a resistivity of 1–150 Ωcm using a Veeco turbodisc maxbright metal-organic chemical vapor deposition (MOCVD) system. The structure is shown in Fig. 1. At first, a 200-nm AlN nucleation layer was grown directly on the top of the Si substrate. Then, several AlGaIn layers as TLs were grown on top of it, followed by a 1.7 μm n-type GaN with $\sim 4 \times 10^{16} \text{ cm}^{-3}$ silicon doping concentration. Then, a GaN layer with a nominal thickness of 300 nm and with different carbon doping concentration was grown by changing the growth temperature. The carbon doping concentrations N_C are: $\sim 7 \times 10^{19} \text{ cm}^{-3}$ (named Sample Run1), $\sim 2 \times 10^{19} \text{ cm}^{-3}$ (Run2), $\sim 6 \times 10^{18} \text{ cm}^{-3}$ (Run3), and $\sim 2 \times 10^{18} \text{ cm}^{-3}$ (Run4), which were measured by secondary ion mass spectrometry (SIMS) from the samples. The thickness of the GaN:C layer shows a slight difference between these four samples due to the different growth conditions required for achieving the target carbon doping concentration. The actual GaN:C thicknesses of the four samples extracted from the *in situ* reflectivity measurement are 285, 278, 275, and 268 nm, respectively. The Si doping concentration of the GaN:Si layer was also confirmed by SIMS measurement and an active electron density of $\sim 4 \times 10^{16} \text{ cm}^{-3}$ was obtained from Hall measurement from a reference sample without the GaN:C layer on top of the GaN:Si layer.

To avoid the impact of the TL/substrate and to have a direct insight of the GaN:C layer, a semivertical diode was fabricated with top–top contacts. Device fabrication commenced with isolation region etching. A 600-nm deep mesa was etched by Cl_2 -based inductively coupled plasma to expose the GaN:Si layer. Then, the ring-shaped ohmic contact metal

Fig. 2. C - V characteristics of samples Run1–Run4 with an ac signal frequency of 1 MHz. Inset: $1/C_{\text{GaN:Si}}^2$ versus V_{Bias} curves of samples Run1–Run4.

stack Ti/Al/Ti/Au (20/100/20/60 nm) was evaporated on it, followed by annealing at 550 $^{\circ}\text{C}$ for 90 s in N_2 ambient. The ohmic contact resistance is around 2 Ωmm , determined by the ring transfer length method. At last, the circular-shaped anode metal contacts of 200 μm in diameter were fabricated by evaporation of a Ti/Au (50/200 nm) bilayer. Fig. 1 shows the cross-sectional schematic of the devices.

In order to investigate the carrier transport mechanism and defect characteristics of the carbon-doped GaN layer with different carbon doping concentration, capacitance–voltage (C - V), current–voltage (I - V), and DLTS measurements were performed.

III. RESULTS AND DISCUSSION

A. Capacitance–Voltage Characteristics

The room temperature C - V measurements were conducted between the anode and ohmic contacts with an ac signal frequency of 1 MHz, which is high enough to ensure that the corresponding time is faster than the trap response time or time constant due to the parallel conductivity. The bias voltage was swept from -10 to 10 V (Run1, Run2, and Run3)/ 5 V (Run4), with a slow sweep ramp rate of 50 mV/s, ensuring the trap occupancy to follow the dc bias voltage. The maximum forward bias voltages are different because the Run1–Run4 devices become conductive at higher bias voltage.

The C - V curves for the four samples are shown in Fig. 2. All the samples show depletion like C - V behavior for a V_{Bias} below around 2.7 V, and a capacitance plateau behavior when V_{Bias} is above 2.7 V bias. Taking account of the plateau capacitance and low conductance under forward bias, the GaN:C layer is seen as a semi-insulating layer. The measured small-signal capacitance C of Run1–Run4 can be expressed as a series connection of $C_{\text{GaN:Si}}$ and $C_{\text{GaN:C}}$ [20]

$$\frac{1}{C} = \frac{1}{C_{\text{GaN:Si}}} + \frac{1}{C_{\text{GaN:C}}}. \quad (1)$$

By deriving the $1/C_{\text{GaN:Si}}^2$ versus V_{Bias} curves, the Si doping concentration of the n-type GaN layer is 4.9 – $5.8 \times 10^{16} \text{ cm}^{-3}$, which is consistent with the target value, indicating that the capacitance depletion result from the n-type GaN layer.

Fig. 3. Double sweep (a) forward and (b) reverse I - V characteristics of the samples Run1-Run4 at room temperature.

B. I - V Characteristics

Double sweep I - V measurements were performed on the four samples at room temperature. The reverse and forward I - V measurements were conducted separately to eliminate the impact of the forward and reverse bias on each other, giving rise to a “memory” effect by charge trapping and slow trap response. The forward bias was swept from 0 to 20 V and then back to 0 V with a voltage ramp rate of 100 mV/s. The reverse bias was swept from 0 to -20 V and then back to 0 V with the same voltage ramp rate.

Fig. 3(a) shows the forward I - V curves of the samples from Run1 to Run4. The Run1 and Run2 show similar behavior, with a fast current increase before 1.5 V followed by a plateau, and then a gradual increase at higher forward bias. Run 3 shows a similar I - V behavior before 1.5 V as Run1 and Run2. However, when the bias voltage continues to increase, the forward current remains almost constant, and when the bias voltage reaches around 10 V, the current shows a steep increase, which is likely to be a device turning-on behavior instead of a hard breakdown by checking the reproducibility of the I - V behavior. Run4 shows a rapid current rise under

forward bias voltage, suggesting a poor blocking ability at forward bias. The double sweep I - V hysteresis is complicated, as shown in Fig. 3(a). All the four samples show a clockwise hysteresis under low forward bias voltage (Run1 and Run2: 0–2.7 V, Run3: 0–6.2 V, and Run4: 0–2.2 V). While with the forward bias voltage increasing, the I - V curves show counterclockwise hysteresis, indicating hole capture in the devices in this region. Note the hysteresis of Run3 and Run4 tends to decrease when increasing the ramping time (not shown here). This time-related turn-on behavior might relate to bistability between the ON-state filamentary conduction [21] and SCLC. The complicated forward I - V behavior can be interpreted with the help of the DLTS measurements and I - V characteristics at different temperatures, which will be discussed in Sections III-C and III-D.

Fig. 3(b) shows that all four samples exhibit a low leakage current under reverse bias. The reverse I - V curves show a counterclockwise hysteresis, suggesting that the devices trap electrons under high reverse bias. It was within expectations because electrons can be injected from the metal into the GaN:C layer under the reverse bias that will be captured by traps, as shown in the inset of Fig. 3(b). The electron capture process has been discussed in detail in [22].

C. DLTS Characteristics

In Sections III-A and III-B, Run1 and Run2 show very similar I - V and C - V characteristics; therefore, here, we only discuss the DLTS results on samples Run2, Run3, and Run4 to investigate the carrier trapping behavior and the defects existing in the GaN:C layer with different carbon doping concentration. Fig. 4 shows the DLTS spectra for these three samples. Obviously, different DLTS signal shape and polarity are observed for a filling pulse voltage V_P at low and high forward bias, respectively. The applied reverse voltage V_R , the duration of the pulse voltage T_P , and the rate window T_W of the curves are shown in Fig. 4.

Fig. 4(a) reveals that only negative peaks related to electron traps are detected in all three samples when the V_P is biased at a low forward voltage ($V_P = 5, 5,$ and 2 V for Run2, Run3, and Run4, respectively). It suggests that electron capture is the dominant process at low forward voltage bias. As clearly seen in Fig. 4(a), the electron traps, labeled E1 and E2, are observed in all the three samples. We noticed that the peak height, proportional to the trap concentration, does not scale with the carbon doping concentration, which means that the electron traps E1 and E2 are not carbon-related defects. They most likely correspond with intrinsic defects. The Arrhenius data are obtained by changing the rate of window T_W . The extracted energy level corresponding to the conduction band edge ($E_C - E_T$) and electron capture cross section (σ_n) of E1 are 0.22–0.31 eV and 3×10^{-17} – 9×10^{-19} cm², respectively. A similar energy level and capture cross section for E1 are commonly observed in GaN grown using different techniques, such as MOCVD [23], HVPE [24], MOVPE [25], and MBE [26]. Alfieri and Sundaramoorthy [27] suggest that this defect is associated with a divacancy ($V_{Ga} - V_N$), while Honda *et al.*'s [28] results have clearly shown that the concentration of this defect is not affected by the presence of impurities, such as

Fig. 4. Temperature-scan DLTS for samples Run2, Run3, and Run4 with (a) low forward pulse voltage and (b) high forward pulse voltage. A T_P of 1 ms, a T_W of 9.5 Hz, and a V_R of 0 V were used.

carbon. In addition, correlation to a pure edge dislocation [29] and a line defect related to native defects, such as O_N , which are strongly bonded along threading dislocation core sites [30], are also suggested. In our case, by changing the pulse time T_P (not shown in here), the trap E1 shows a logarithmic filling behavior and a fixed peak position, suggesting it is an extended defect with localized states [31], [32]. The parameters of the trap E2 cannot be precisely defined due to overlap with the other peaks. Nevertheless, from the literature, we found that a peak similar to E2 located around 300 K is commonly observed, accompanying E1. For example, both were observed in undoped [33], n-type [29], and carbon-doped GaN layers [34], [35]. The trap E2 is thought to be associated with the Ga antisite defect (N_{Ga}).

For Run2, another negative peak labeled E3 and located at temperatures over 400 K can be observed in the DLTS spectrum. We can see that the peak height of E3 should be much higher than for E1 and E2, indicating the trap concentration of E3 is very high, and it should have a significant impact on the device's electrical behavior. E3 is thought to correspond with a C-related defect because the only difference between Run3,

Fig. 5. Schematic of the charge exchange between two defects (orange) instead of between defects and E_V (blue).

Run4, and Run2 is the carbon concentration. Note that E3 is only observed in the sample Run2 with a carbon concentration over $2 \times 10^{19} \text{ cm}^{-3}$ and whose I - V curves also show totally different behavior compared with the samples with $N_C < 2 \times 10^{19} \text{ cm}^{-3}$, implying that the E3 defect begins to dominate the I - V and C - V characteristics. Limited by the measurement equipment, the maximum temperature of the DLTS system is 400 K; therefore, the energy level and capture cross section of E3 cannot be derived yet. However, by monitoring the admittance transient at 1 MHz and at different temperatures, an electron trap with activation energy $\Delta E_A = 0.29 \text{ eV}$ and $\sigma = 3 \times 10^{-24} \text{ cm}^2$ is extracted (not shown here). The unusual small electron capture cross section indicates that the carrier capture and emission processes may happen between two different defects, instead of between a defect and the valence band edge (E_V), as shown in Fig. 5. In the defect band model proposed by Koller *et al.* [22], the C_N deep acceptors exchange charges with a defect band, and carriers can transport along with the defect band. This model fits well with our experimental results.

Fig. 4(b) shows the DLTS spectra of Run2, Run3, and Run4 for a V_P bias at a high forward voltage ($V_P = 12, 10$, and 6 V for Run2, Run3, and Run4, respectively). For Run3 and Run4 ($N_C < 1 \times 10^{19} \text{ cm}^{-3}$), the devices turn on at the corresponding V_P , as shown by the I - V curves in Fig. 3, and a positive signal peak, labeled H1, is shown in the DLTS spectrum. This suggests holes exist in the devices and are captured when the device is biased at high V_P . For the structure in Fig. 1, this hole injection occurs from the metal into the GaN:C layer under high positive V_P conditions. Extracted from the Arrhenius plot, the energy level of H1 is 0.47 eV , with $\sigma = 3 \times 10^{-17} \text{ cm}^2$, which is associated with the C_N induced donor-like traps with $(0/+)$ state [36]–[39].

For Run2, considering the device reliability, the maximum V_P applied is 12 V . The device is under OFF-state at this voltage; therefore, there are a few holes injected into the GaN:C layer, which can be neglected when compared with the electron capture process, resulting in the absence of the positive hole peak in the DLTS spectrum of Run2. In contrast to Run3 and Run4, the negative peak of the E3 defect is observed in the DLTS spectrum of Run2 with $V_P = 12 \text{ V}$ and the amplitude can be expected higher than the amplitude of H1, indicating there is a large amount of electron capture.

Fig. 6. Forward I - V curves of (a) Run1, (b) Run2, (c) Run3, and (d) Run4.

D. Carrier Transport Mechanism

To investigate the carrier transport mechanism in the GaN:C layer with different carbon concentrations, I - V measurements were performed at different temperatures. Fig. 6 shows the forward I - V curves at different temperatures, from 25 °C to 150 °C with a temperature step of 25 °C. It is observed that the samples with high (Run1 and Run2) and low (Run3 and Run4) carbon doping concentration show obviously different I - V behavior with temperature changing. Therefore, we will discuss them separately.

1) *Samples Run1 and Run2* ($N_C > 2 \times 10^{19} \text{ cm}^{-3}$): The samples Run1 and Run2 show similar I - V characteristics with increasing temperature; here, we will only discuss the carrier transport mechanism for the Run1 case. The leakage currents of Run1 show a rapid increase from 0.5 V to around 1.5 V (depending on the temperature), and then transform to a gradual increase, and therefore, the leakage mechanisms are different in these two regions. Fig. 7(a) shows the log-log plot of the forward I - V curves of Run1. The suddenly increasing currents follow a power-law relation with bias voltage very well:

$$J \propto V^m \quad (2)$$

which can be modeled by an SCLC mechanism with traps [40]. Before the SCLC current, the transport mechanism is dominated by ohm's law, where the injected carrier density (n_{inj}) is lower than the free carrier density (n_0). With bias voltage increasing, $n_{inj} > n_0$, the injected carriers are captured by traps, where the SCLC mechanism may dominate [41].

In the 2–20-V voltage range, the currents gradually increase with increasing bias voltage and are highly dependent on temperature. In this region, P-F emission [42], [43] and variable-range hopping (VRH) [44] may both dominate. The relation between the current density J and the electrical field strength E of the P-F emission mechanism can be

Fig. 7. (a) Log-log I - V curves of Run1. The m used in the fitting is 4–5 for different temperatures. (b) $\ln(J/E)$ versus $\sqrt{E}$ curves of Run1.

Fig. 8. (a) $\ln(J)$ versus $1/T^{0.25}$ curves of Run1 at fixed bias voltage of 8, 10, 12, 15 V. (b) Band diagram and carrier transport mechanism of Run1 and Run2 under forward bias.

expressed as

$$J \propto E \exp \left(- \frac{q \left(\phi_B - \sqrt{\frac{qE}{\pi \epsilon_r \epsilon_0}} \right)}{k_B T} \right) \quad (3)$$

where $q\phi_B$ is the trap energy level, k_B is Boltzmann's constant, and T is the temperature. Fig. 7(b) shows that the forward current behavior of Run1 follows a good linear relation between $\ln(J/E)$ and $\sqrt{E}$ at all temperatures. The extracted barrier heights by fitting the curves with the P-F emission mechanism using (3) vary from 0.9 to 1.1 eV from 25 °C to 150 °C. However, the electrical field strength at the bias voltage is low, i.e., $< 1 \text{ MV/cm}$, which makes it difficult for carriers to get enough energy to jump over the high barrier. Therefore, VRH could be the dominant mechanism in this region [44], where the conduction follows:

$$J \propto \exp \left(- \left(\frac{T_0}{T} \right)^{\frac{1}{4}} \right). \quad (4)$$

Fig. 8(a) shows the forward current at different bias voltage as a function of $1/T^{0.25}$. The curves are fitted linearly well. The extracted T_0 is around $4 \times 10^8 \text{ K}$, which is in good agreement with Koller *et al.*'s [22] value of 10^8 K . Besides, the VRH transport mechanism in the GaN buffer layer was commonly found in other articles with carbon doping concentration over $1 \times 10^{19} \text{ cm}^{-3}$ [16], [22]. Fig. 8(b) shows the band diagram and summarizes the carrier transport mechanisms of Run1 and Run2 under forward bias.

2) *Samples Run3 and Run4* ($N_C < 1 \times 10^{19} \text{ cm}^{-3}$): Compared with Run1 and Run2, a turn-on behavior was observed both for Run3 and Run4. Fig. 9 shows the log-log scale I - V curves of Run3 and Run4. Here, we give a detailed discussion for the sample Run3.

Fig. 9. Forward I - V curves of (a) Run3 and (b) Run4 in log-log scales at different temperature. The carrier transport mechanisms in each region of Run3 are labeled.

Fig. 10. Band diagram and carrier transport mechanisms (a) before and (b) after the device turning on.

In the 0–0.7-V bias voltage range, the current behavior follows ohm's law, exhibiting a linear relation on a log-log scale. In the voltage range from 0.7 to 2 V, the current increases quickly and shows a power-law relation with bias voltage, which can also be modeled by an SCLC mechanism with traps. When the bias voltage rises above 2 V, the slope of the current suddenly decreases, which means another transport mechanism comes into play. In the 2–10-V voltage range, the current keeps almost unchanged with increasing bias voltage and just depends on temperature. This can be interpreted by the band diagram in Fig. 10(a). As shown by the I - V hysteresis and DLTS results, electrons are trapped in defects under this forward bias. The current in this voltage range is dominated by the carrier transport between defects. We consider that the defects (located at the interface of GaN:C/GaN:Si or in the GaN:C layer near the interface) are filled by electrons, leading to a potential barrier. This phenomenon is commonly named the pinning effect. Therefore, the electrons in the GaN:Si layer and the holes in the GaN:C layer have to overcome the barrier to contribute to the current. With the bias increasing, more holes are injected into GaN:C layer from metal. Some defects begin to capture holes, causing the barrier height to decrease quickly. The electrons in the GaN:Si layer and the holes in the GaN:C layer then can easily overcome the barrier, and the device turns on steeply. In addition, despite the holes capture mechanism, we would like to notice that other trap- and field-related mechanisms can be considered leading to the device turning on [21].

When the device turns on, a high density of holes is injected into the GaN:C layer and captured by the donor-like traps in the GaN:C bulk. This is supported by the observed

high positive peak (hole trap H1) in the DLTS spectra when V_P is biased at high forward voltage [Fig. 4(b)] and the big counterclockwise I - V hysteresis in Fig. 3(a). Fig. 10(b) shows the band diagram and carrier transport mechanisms after the device turn-on.

The sample Run4 ($N_C = 2 \times 10^{18} \text{ cm}^{-3}$) shows a weak current blocking capability at forward bias voltage. The leakage current exhibits similar behavior with Run3, despite a short-voltage-independent region and earlier device conduction, which results from a lower defect concentration to pin the Fermi level.

IV. CONCLUSION

In this work, a Metal/GaN:C/GaN:Si structure is used to investigate the defect charging process and carrier transport mechanisms in the GaN layer with different carbon doping concentration. Obviously, different forward I - V behavior is observed between the samples with high ($N_C > 1 \times 10^{19} \text{ cm}^{-3}$) and low ($N_C < 1 \times 10^{19} \text{ cm}^{-3}$) carbon concentration. For the samples with high carbon concentration, Run1 and Run2, Ohm's law, SCLC, and VRH may dominate the carrier transport mechanism in sequence when increasing the forward bias. For the samples with low carbon concentration, Run3 and Run4, besides the above carrier transport mechanism, a sudden device turning on behavior was observed. In addition, it is found that carbon introduces electron traps at or near the GaN:C/GaN:Si interface, which results in a strong pinning effect and builds up a barrier impeding carrier injection. Different DLTS spectra are also observed between samples with high and low carbon concentration. The samples with high N_C exhibit a high density of electron traps in the whole forward bias range, which is interpreted by defects exchanging charges with a defect band. While the samples with low carbon doping concentration show an electron trap at low bias voltage and a hole trap at high bias voltage, resulting from defects exchanging charges with the valence band.

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