Dispersive Effects in Microwave AlGaN/AlN/GaN HEMTs With Carbon-Doped Buffer

Sebastian Gustafsson, Student Member, IEEE, Jr-Tai Chen, Johan Bergsten, Urban Forsberg, Mattias Thorsell, Member, IEEE, Erik Janzén, and Niklas Rorsman, Member, IEEE

Abstract—Aluminium gallium nitride (AlGaN)/GaN high-electron mobility transistor performance is to a large extent affected by the buffer design, which, in this paper, is varied using different levels of carbon incorporation. Three epitaxial structures have been fabricated: 1) two with uniform carbon doping profile but different carbon concentration and 2) one with a stepped doping profile. The epitaxial structures have been grown on 4H-SiC using hot-wall metal–organic chemical vapor deposition with residual carbon doping. The leakage currents in OFF-state at 10 V drain voltage were in the same order of magnitude (10^{-4} A/mm) for the high-doped and stepped-doped buffer. The high-doped material had a current collapse (CC) of 78.8% compared with 16.1% for the stepped-doped material under dynamic I–V conditions. The low-doped material had low CC (5.2%) but poor buffer isolation. Trap characterization revealed that the high-doped material had two trap levels at 0.15 and 0.59 eV, and the low-doped material had one trap level at 0.59 eV.

Index Terms—Current collapse (CC), dispersion, gallium nitride (GaN), high-electron mobility transistor (HEMT), trap levels.

I. INTRODUCTION

GALLIUM nitride (GaN)-based high-electron mobility transistors (HEMTs) offer exceptional high frequency and power performance due to its high-electron mobility and wide bandgap. In terms of traditional high-frequency figures of merit GaN devices have matured in the last decade, reaching $f_t/f_{\text{max}}$ of up to 450/600 GHz [1] and output power up to 40 W/mm [2].

High output power is enabled by a highly semi-insulating buffer, which improves breakdown characteristics, minimizes buffer leakage, and short-channel effects [3]. Buffer isolation can be achieved using intrinsic growth defects to form deep donors and acceptors [4]. This approach yields highly resistive (HR) buffers but at the expense of crystal quality. Alternatively, an intentional dopant, such as iron (Fe), carbon (C), or magnesium (Mg), enables HR buffers without compromising crystal quality [5], [6]. Both procedures introduce trap states which may reduce the ON-state conductance and maximum drain current under dynamical conditions, effectively limiting the RF output power and efficiency [7].

The most commonly used buffer dopant is Fe, which suffers from memory effects during growth, rendering arbitrary design of the doping profile impossible [6]. The carbon doping process lacks such memory effects, making it possible to have discontinuous C-doping profiles and sharp transitions to the GaN channel [8]. However, simulations on carbon-doped HEMTs indicate a problem where the buffer can become floating, possibly pinching the active channel [9]. Nevertheless, both iron and carbon doping suffer from severe current collapse (CC) if the compensation-doped buffer is placed close to the GaN channel [10]–[13]. Several reports show that the doped buffer should be placed at a sufficiently long distance from the GaN channel to reduce CC [10], [14]. The optimal buffer design is a tradeoff between several HEMT characteristics (e.g., breakdown voltage, short-channel effects, subthreshold leakage, CC, and maximum drain-source current) and may vary for different applications.

In this paper, we have fabricated three types of AlGaN/AlN/GaN:C HEMTs with different carbon doping concentration and profile. A comprehensive characterization, including dc, small signal RF, and large signal RF, has been carried out in order to evaluate the device performance, focusing on microwave power amplifiers. Trap characterization has been carried out using pulsed I–V, drain current transient (DCT), and conductance dispersion measurements. This paper will also form a foundation for physical device simulations to further understand carbon trapping phenomena, and to optimize the carbon doping profile in the buffer.

This paper is organized as follows. Material growth and the HEMT fabrication process is covered in Section II. The device characterization and measurements are presented in Section III. Finally, the conclusion is drawn in Section IV.

II. EXPERIMENT

A. Growth of AlGaN/AlN/GaN Heterostructures on SiC

The epitaxial structures were grown by a hot-wall metal–organic chemical vapor deposition system [15], [16].
The heterostructure consisted of a 100-nm high-temperature AlN nucleation layer, a thick GaN layer with different carbon doping profiles followed by a 2-nm AlN exclusion layer, and an undoped AlGaN layer grown on semi-insulating 4H-SiC. The carbon doping in the GaN layer was realized using residual carbon impurities, which is controlled by the growth temperature [17]. Four different carbon levels were utilized in this paper, i.e., $1 \times 10^{17}$, $1 \times 10^{18}$, $1 \times 10^{19}$ cm$^{-3}$, and $1 \times 10^{20}$ cm$^{-3}$ that were prepared at the growth temperatures of 980 °C, 1000 °C, 1040 °C, and 1080 °C, respectively. Three epiwafers were grown to study the dispersion and memory effects, denoted as High-C, Low-C, and Stepped-C. The structural parameters and carbon profiles of the epiwafers are shown in Fig. 1. Two single-level carbon profiles were designed for the GaN layers in High-C and Low-C, respectively. The Stepped-C wafer contains a three-level carbon profile.

The crystalline quality of the three epiwafers was assessed by high-resolution X-ray diffraction rocking curve measurements. The values of full width of half maximum of the GaN (102) peaks for High-C, Low-C, and Stepped-C were 365, 282, and 436 arcsec, respectively. The sheet resistance was measured using a noncontact eddy-current technique. The mobility and the sheet carrier density were determined using a noncontact low-power microwave reflectance technique supplied by Lehighton on the center position of each epiwafer (Table I) [18].

### III. RESULTS

This section describes and discusses the HEMT measurements. The Stepped-C device has a different layout and structure compared with the Low-C and High-C devices, which has been accounted for where necessary. Overall, the Stepped-C HEMT has lower parasitic resistance due to shorter source–drain distance.

#### A. Hall

After processing, Hall measurements were performed using a Hall effect measurement system (HL5500PC, Biorad). The measured quantities are in good agreement with the preprocessing measurements (Table I). The passivation-first process, with a high-quality SiN$_x$ combined with a low-temperature ohmic contact anneal, preserves the mobility and electron density. However, the High-C structure showed a large nonuniformity. This is likely associated with nonuniform carbon distribution over the epiwafer. As mentioned in Section II-A, the residual carbon from the growth chamber and the precursor itself (tri-methyl gallium) were utilized as the carbon source. The carbon incorporation rate was controlled by the growth conditions. Therefore, the uniformity of the carbon doping depends greatly on the temperature and deposition profiles in the growth zone. In this investigation, no focus has been in optimizing the carbon

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**Table I**

<table>
<thead>
<tr>
<th>Material</th>
<th>$R_{\text{sh}}$ ($\Omega/cm$)</th>
<th>$\mu$ ($\text{cm}^2/\text{V} \cdot \text{s}$)</th>
<th>$n_s$ ($10^{13} \text{cm}^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before processing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-C</td>
<td>373</td>
<td>1550</td>
<td>1.10</td>
</tr>
<tr>
<td>Low-C</td>
<td>270</td>
<td>1960</td>
<td>1.21</td>
</tr>
<tr>
<td>Stepped-C</td>
<td>356</td>
<td>1735</td>
<td>1.00</td>
</tr>
<tr>
<td>After processing</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-C</td>
<td>373-437</td>
<td>1470-1730</td>
<td>0.97</td>
</tr>
<tr>
<td>Low-C</td>
<td>272</td>
<td>1980</td>
<td>1.16</td>
</tr>
<tr>
<td>Stepped-C</td>
<td>305</td>
<td>1640</td>
<td>1.25</td>
</tr>
</tbody>
</table>

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**Fig. 1.** Specification of the epitaxial design. (a) High-C. (b) Low-C. (c) Stepped-C. Figures are not to scale.
uniformity over large area. Since carbon is known for its adverse impact on two-dimensional electron gas properties, it is reasonable to attribute the variance of $R_{sh}$ to the uniformity of the carbon distribution. The mobility of the Stepped-C wafer was not as high as expected, and the mechanism is not completely understood. However, it should be noted that its AlGaN structure contained a high Al content, 30%, that accordingly built up high strain on the GaN, which might give rise to an early partial relaxation of the AlGaN, leading to a degraded mobility.

**B. DC**

TLM measurements were performed on three positions on each wafer (Table II). All materials show a similar contact resistance ($R_c$), demonstrating the feasibility of a repeatable recessed ohmic contact process. The $R_{sh}$ after device fabrication is in good agreement with the preprocess and Hall measurements (Table I).

The $I–V$ characteristics were measured with a parameter analyzer and are shown in Fig. 2(a) and (b). A significantly lower leakage current is seen for devices with a high and stepped carbon doping. The higher gate leakage for the low-doped device can be affiliated with the pinch-off voltage, which is more negative compared with the high-doped device. This will increase the slope of the energy band in the AlGaN/GaN interface. Therefore, electron tunneling is more prominent, effectively increasing the gate leakage. Drain-induced barrier lowering (DIBL) is comparably small for the Stepped-C and High-C devices, but severe for the Low-C device [Fig. 2(b) (inset)]. For Low-C HEMTs, the threshold voltage is continuously lowered as the drain voltage increases and drops dramatically beyond 30 V. This can be explained by high-energy electron injection into the buffer. Table III contains extracted values of the subthreshold slope ($SS$), ON-resistance ($R_{on}$), saturated drain current ($I_dss$), transconductance ($g_m$), and DIBL. As expected the $SS$ is higher for devices with better electron confinement (High-C and Stepped-C). The variation in ON-resistance between the devices is due to differences in $R_{sh}$, $R_c$, and the device layout. The lower saturation current and transconductance for the High-C device can be attributed to the lower carrier density and carrier mobility in the material. The Low-C and Stepped-C devices are comparable in terms of saturation current, while Stepped-C has slightly higher transconductance.

Breakdown was measured using a drain current injection technique [21] [Fig. 2(c)]. A sharp step is seen at the pinchoff voltage for the High-C and Stepped-C materials. The step is followed by a slope, where channel breakdown occurs. Eventually, gate breakdown occurs in the last region where $V_{DG}$ saturates. The measurement of the Low-C material shows a different behavior with no sharp transitions. This is explained by the electron injection in the low-doped buffer, and the majority of the drain current in this device is leaking through the buffer.

**C. S-Parameters**

S-parameters were measured from 10 MHz to 110 GHz. The measured $S_{11}$, $S_{22}$, $|U|$, and $|h_{21}|$ at the bias point with
maximum $f_T$ are shown in Fig. 3. The devices have similar small signal behavior in terms of input and output impedance, while the device with Stepped-C has noticeably higher gain than devices with High-C and Low-C. Table IV summarizes the small signal characterization in terms of maximum $f_T$, maximum $f_{\text{max}}$, extrinsic $g_m$, extrinsic $g_{ds}$, and extrinsic $C_{\text{out}}$ extracted at bias point for max $f_T$.

<table>
<thead>
<tr>
<th>Material</th>
<th>$f_T$ (GHz)</th>
<th>$f_{\text{max}}$ (GHz)</th>
<th>$g_m,\text{ext}$ (mS/mm)</th>
<th>$g_{ds,\text{ext}}$ (mS/mm)</th>
<th>$C_{\text{out}}$ (pF/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-C</td>
<td>27</td>
<td>61</td>
<td>282</td>
<td>23.2</td>
<td>0.57</td>
</tr>
<tr>
<td>Low-C</td>
<td>32</td>
<td>92</td>
<td>298</td>
<td>23.5</td>
<td>0.67</td>
</tr>
<tr>
<td>Stepped-C</td>
<td>46</td>
<td>146</td>
<td>390</td>
<td>26.6</td>
<td>0.71</td>
</tr>
</tbody>
</table>

The Stepped-C device shows the best performance in terms of $f_T$ and $f_{\text{max}}$, mostly due to its different layout and structure. The output capacitance and output conductance are similar for all devices, and the extracted transconductance shows reasonable agreement with the values obtained from the dc characterization.

**D. Output Conductance Dispersion**

An investigation of the output conductance dispersion was performed by measuring low-frequency Y-parameters at different ambient temperatures. This enables extraction of the activation energies of trap states [22]. The temperature was swept from 20 °C to 160 °C. Calibrated two-port Y-parameter measurements were made from 5 Hz to 3 GHz with the quiescent drain current set to 15% of $I_{\text{DSS}}$. The quiescent drain voltage was adjusted so that the dissipated power was equal to 0.1 W, resulting in low self-heating.

The measurements are shown in Fig. 4. The High-C device is suffering from severe dispersion with two prominent peaks and the Low-C device is showing similar dispersion at low frequencies as the High-C device. The Stepped-C device shows the best performance in terms of $f_T$ and $f_{\text{max}}$ mostly due to its different layout and structure. The output capacitance and output conductance are similar for all devices, and the extracted transconductance shows reasonable agreement with the values obtained from the dc characterization.

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The measurements are shown in Fig. 4. The High-C device is suffering from severe dispersion with two prominent peaks and the Low-C device is showing similar dispersion at low frequencies as the High-C device. The activation energies of traps $E_2$ and $D_1$ are extracted from an Arrhenius diagram (Fig. 5); $E_2 = 0.59$ eV and $D_1 = 0.15$ eV. Traps associated with the $E_2$ activation energy are interesting because this trap level is also found in devices with iron doping. It is speculated that this trap is related to defects in the GaN material, which is dependant on the buffer doping concentration. The physical origin of the trap is not determined, but can be due to either impurities or intrinsic defects, such as vacancies or antisites [23]. The $D_1$ trap is also related to defects and dislocations in the GaN material [24].
Fig. 5. Arrhenius plot for identified traps in the dispersion measurements.

Fig. 6. DCT measurement showing the drain current derivative with respect to logarithmic time. Inset: DCT normalized with the quiescent current versus logarithmic time.

In [25], a trap with similar activation energy (0.18 eV) is found, and is suggested to be located at the surface. The Stepped-C device does not show any consistent shift in the dispersion peaks versus frequency and no activation energy could, therefore, be extracted.

E. Drain Current Transient

Trapping time constants were investigated using an oscilloscope-based DCT measurement setup. The gate was biased at a constant voltage, setting the quiescent drain current to 25% of $I_{DSS}$. The drain voltage was pulsed from $V_{DSQ}$ to $2 \cdot V_{DSQ}$. Measurements with this pulse type and bias point will probe channel trapping and deep buffer traps under ON-state device operating conditions. The drain voltage is normalized to consider the different layout of the Stepped-C device.

Application-like conditions were invoked by having a short and periodic trap filling pulse. The trap filling pulse was 10-µs long and the period time was set to 1 s to facilitate full recovery of the drain current. The drain current was monitored from 1 µs to 10 ms. The measured DCT is shown in Fig. 6 (inset). A trap with an emission time of $\sim 50$ µs is observed for both the High-C and the Low-C materials. However, the high-doped material also has a trap with an emission time of $\sim 1$ ms, indicating the presence of another trap level. This is in line with the trap state characterization in Section III-D. Even though no trap levels were identified for the Stepped-C material in Section III-D, it has a large peak emission at $\sim 0.3$ ms. The amplitude of the current lag is higher than for the other materials and may be due to errors in normalization of the quiescent voltages, but does not effect the qualitative analysis.

F. Pulsed I–V

CC and knee walkout effects were characterized using a dynamic $I–V$ analyzer (Accent D225). The pulselength was set to 1 µs with a 1 ms period time. The gate voltage was pulsed from $-6$ to 1 V in 0.5 V steps and the drain voltage was pulsed from 0 to 15 V in 0.1 V steps. This measurement was carried out to investigate surface trapping and deep buffer trapping under OFF-state quiescent conditions.

The magnitude of the CC is given by the slump ratio defined as

$$Z(V_{GSQ}, V_{DSQ}) = \frac{I_{DS}|_{V_{GSQ}, V_{DSQ}} - I_{DS}|_{0,0}}{I_{DS}|_{0,0}} \cdot 100$$

(1)

where $I_{DS}|_{V_{GSQ}, V_{DSQ}}$, and $I_{DS}|_{0,0}$ are the drain current measurements with a quiescent state of ($V_{GSQ}$ and $V_{DSQ}$) and (0 and 0), respectively. The drain currents used for calculating the slump ratio are taken from readings within parentheses.
at $V_{GS} = 1$ V and $V_{DS} = 10$ V. The current slump and dynamic $R_{ON}$ is given for two quiescent states in Table V. The slump ratio versus $V_{DSQ}$ and $V_{GSQ}$ is shown in Fig. 7. The dynamic $I_{DS}$–$V_{DS}$ characteristics for five different quiescent states are shown in Fig. 8.

The High-C device exhibits a major CC and drops to $\sim 75\%$ of the reference current, while the Low-C device has very slight CC throughout the $V_{DSQ}$ stepping. The Stepped-C HEMT shows similar $V_{DSQ}$ dependence as the Low-C device. However, the Stepped-C device has larger CC due to the drop in drain current when a nonzero quiescent gate voltage is applied. The current slump performance of the Stepped-C device is not entirely in line with the DCT measurements, which might be due to the normalization in the DCT measurements. The significant increase in $R_{ON}$ for the high-doped device confirms that the $D_1$-trap is located on the surface.

The use of carbon doped buffer in [9] is shown to form a floating p-n junction, causing severe dispersion. The characterizations carried out in this paper indicates that the dispersion of C-doped GaN HEMTs is not as severe, and in line and even better than the previous work on Fe-doped buffers. The dispersion in C-doped buffers might, therefore, be due to other defects in the crystal not considered, but discussed, in [9]. A recent meta study on iron-doped buffers has found a trap with an activation energy of 0.6 eV, which is not directly related to the Fe-atoms in the buffer [13]. In this paper, we have found a trap with a similar activation energy ($E_2 = 0.59$ eV). We also observe another defect-related surface trap in the high-doped HEMT with an activation energy of

G. Load-Pull

Large signal device characterization was carried out using an active load-pull setup [27] at a fundamental frequency of 3 GHz. The devices were biased in Class AB, with a quiescent current of 15% of $I_{DSS}$ and $V_{DSQ} = 15$ V.

An input power sweep was carried out for each device with the load impedance optimized for maximum output power, and the corresponding output power and drain efficiency is shown in Fig. 9. The Low-C and Stepped-C devices show comparable performance and deliver similar output powers. The gain is slightly higher for the Stepped-C device, resulting in higher drain efficiency at lower input powers and earlier saturation. As expected from the previous measurements, the large signal RF performance of the High-C device is degraded due to the severe CC, effectively lowering the output power and drain efficiency. The maximum obtained output power is in good agreement with estimations from pulsed $I$–$V$ measurements and amount to $\sim 0.9$, 2.4, and 2.3 W/mm for High-C, Low-C, and Stepped-C, respectively.

IV. CONCLUSION

We have shown an extensive characterization of GaN HEMTs fabricated from three different materials with a high, low, and stepped carbon doping profile. Results show that low leakage current and low CC can be achieved by optimizing the doping profile, thus maintaining good large signal RF performance. In consistency with other reports, placing a highly doped buffer close to the GaN channel severely degrades large signal RF performance due to the severe CC, effectively lowering the output power and drain efficiency. The maximum obtained output power is in good agreement with estimations from pulsed $I$–$V$ measurements and amount to $\sim 0.9$, 2.4, and 2.3 W/mm for High-C, Low-C, and Stepped-C, respectively.
$D_1 = 0.15 \text{ eV}$. These traps may explain the different results in this paper and in [9]. Furthermore, as explained in [28], if vertical leakage paths exist between channel and buffer the device can still have low CC.

Trapping effects can be extremely dynamic and sensitive to the stimuli. Depending on application needs, certain measurements can be focused on and different device properties can be emphasized by optimizing the buffer. Carbon is indeed a viable dopant for low-dispersive, HR buffers, and there is room for further development and improvement of the doping profile.

REFERENCES


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