Qualitative and Quantative Characterization of Trapping Effects in 
AlGaN/GaN High Electron Mobility Transistors

Dissertation

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Abstract

GaN-based high electron mobility transistors (HEMTs) have been considered excellent candidates for high power, high speed and high temperature applications due to high breakdown voltage, high electron saturation velocity and high operation temperature. Such superiority of AlGaN/GaN HEMTs leads to power density several times higher than commercially available devices. AlGaN/GaN HEMT power amplifiers have applications for wireless base-station, and communication and military radar systems. Recently, impressive device performances in AlGaN/GaN HEMTs have been reported such as high output power of 40 W/mm at 4 GHz, current gain cut-off frequency ($f_T$) of 190 GHz and power-gain cut-off frequency ($f_{MAX}$) of 230 GHz. However, critical issues including current dispersion and device reliability have limited AlGaN/GaN HEMTs for practical applications. Current dispersion causing decrease in the actual output drain current and voltage swing at RF operations is attributed to surface/interface states in the AlGaN/GaN heterostructures created during material growth and device processing. Even though there have been remarkable improvements in growth/device fabrication technologies, trapping effects in AlGaN/GaN HEMTs cannot be removed perfectly, indicating that an accurate HEMT model including trapping effects is still needed for development of both novel HEMT processing/material growth techniques and implementation of AlGaN/GaN HEMT-based circuits.
In this Ph.D research, we investigated distinct electrical behavior of AlGaN/GaN HEMTs through study on PGA effects using DC and pulsed I-V characterization under different pulse widths and quiescent biases to understand electron capture/emission phenomena. Through the electrical characterization at different measurement conditions Current collapse in AlGaN/GaN was analyzed in terms of trap activities, and impact of PGA effects was qualitatively evaluated as a method for device processing monitoring.

Based on temperature-dependent drain current transients, it was demonstrated that PGA modifies trap activity in AlGaN/GaN HEMTs. The PGA process removes shallow traps with an activation energy of ~ 38 meV and $t_E$ of ~ 0.5 $\mu$s at 295 K and induces deeper traps at least with an activation energy of ~ 0.31 eV and $t_E$ of ~ 21.6 $\mu$s at 295 K. Shallow traps result in fast drain current transient and high reverse gate leakage current while deep traps lead to slow current recovery but a small leakage current.

Electrical behaviors of interface states at metal/AlGaN interface in Ni/AlGaN/GaN Schottky diodes was investigated to discover PGA effects on Ni/AlGaN interface states by comparing EBIC analysis results and electrical characteristics of Ni/AlGaN/GaN diodes. It was showed that the post-annealing reduced the density of the electrically active states at the Schottky metal/AlGaN surface, leading to decrease of reverse leakage current, and $J_S$, and increase of Schottky barrier height. In addition, XPS analyses was performed to investigate if unintentional reaction on free AlGaN surface
was examined during the PGA process since unexpected oxidation on free AlGaN surface by PGA can prevent trapping of electrons injected from reversely-biased gate as the same role of the normal passivation layer. XPS analyses showed that unintentional oxide layer was formed by PGA.

Base on the qualitative trap study, trap characterization methods were developed in terms of device parameters since evaluation of the trapping effect can be easily performed using these parameters. Current dispersion due to electron trapping was characterized in terms of device parameters such as threshold voltage, effective gate length, and parasitic series resistances based on two proposed models. One is zero-drain-bias output conductance method using output conductance with gate bias near zero drain voltage. The other is low-drain-voltage field method using drain current with respect to gate bias at a fixed low drain voltage. It was demonstrated that a higher negative electric field between gate and drain contacts cause a larger current dispersion due to trapping of more electrons, leading to a higher $V_T$ shift in the positive direction, a longer effective gate length, and smaller parasitic resistances. The HEMT modeling was performed only in the linear region of $I-V$ characteristics, so further comprehensive modeling including the saturation region is required.

In summary, we have systematically investigated trapping effects in AlGaN/GaN HEMTs. Current dispersion between DC and pulsed $I-V$ characteristics was analyzed in terms of trap activity at different quiescent bias points with different pulse width showing
that PGA modifies electrical properties of active traps. Optimized PGA removes deep-level traps which are responsible for slow drain current transient. Based on a better understanding of electron capture/emission mechanism, behavioral device models for trap characterization were developed. Current dispersion due to electron trapping was characterized in terms of device parameters in AlGaN/GaN HEMTs. Finally, it is suggested that our methodologies can be applied for AlGaN/GaN HEMT modeling in presence of trapping effects for evaluation of newly-introduced device/growth techniques, monitoring of device fabrication process, and, potentially, circuit applications while further systematic modeling including the saturation region is required.
Dedication

Dedicated to God, our parents,

my dear wife, Yun A Shin and two lovely sons, Sung Won and Yongbum
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Chapter 1: Introduction

This chapter delivers an overview of AlGaN/GaN high electron motility transistors (HEMTs) such as material properties of GaN based materials, HEMT operation principle and electron transfer. In addition, effects of electron trapping on AlGaN/GaN HEMT performances, which are major drawbacks as well as a key research topic in AlGaN/GaN HEMT applications, are introduced with some discussion on possible trapping/detrapping mechanisms. Finally, objectives of my Ph.D. research and the outline of this dissertation are depicted.

1.1 Background and Motivation

GaN-based high electron mobility transistors (HEMTs) have great potential for high power and high frequency applications due to high breakdown voltage, high electron saturation velocity and high operation temperature [1-7]. A plenty of researchers have demonstrated that AlGaN/GaN HEMT power amplifiers are an excellent candidate for microwave/RF applications such as wireless base-stations, next-generation cell phone, satellite communication, military radar systems, etc. as shown in Figure 1.1 [8]. Those wireless/satellite communication and military applications are continuously growing.
markets and require higher-frequency and higher-power amplifiers. Recently, impressive device performances in AlGaN/GaN HEMTs have been reported such as high output power of 40 W/mm at 4 GHz [3], current gain cut-off frequency ($f_T$) of 190 GHz [4] and power-gain cut-off frequency ($f_{MAX}$) of 230 GHz [6].

Still, Si- and GaAs-based field effect transistors have been prevailing in this field although material properties of those materials have limited the scope of their applications in terms of power and speed performance. This is simply because Si- and
GaAs-based devices satisfy current demands of industry and consumers for current applications. However, since demanding power and frequency levels become higher and higher for future commercial/military applications, Si and GaAs are expected to be replaced by some wide-band gap materials that have higher breakdown field and higher saturation velocity. In addition, even now, GaN-based devices currently have advantages for high-cost military applications where device performance is more critical. Table 1.1 shows various material properties of different materials used for microwave and RF applications [9].

Table 1.1 Material parameters related to power performance at high frequencies for various materials [9]. Johnson’s figure of merit is an indicator for power-frequency performance of discrete device and is normalized to that of silicon [10]. Note that all the symbols stand for a meaning in a general nomenclature of device physics.

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>GaAs</th>
<th>4H-SiC</th>
<th>GaN</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_g$ (eV)</td>
<td>1.1</td>
<td>1.42</td>
<td>3.26</td>
<td>3.39</td>
<td>5.45</td>
</tr>
<tr>
<td>$n_i$ (cm$^{-3}$)</td>
<td>$1.5 \times 10^{10}$</td>
<td>$1.5 \times 10^6$</td>
<td>$8.2 \times 10^{-9}$</td>
<td>$1.9 \times 10^{-10}$</td>
<td>$1.6 \times 10^{-27}$</td>
</tr>
<tr>
<td>$\varepsilon_r$</td>
<td>11.8</td>
<td>13.1</td>
<td>10</td>
<td>9.0</td>
<td>5.5</td>
</tr>
<tr>
<td>$E_{br}$ (MV/cm)</td>
<td>0.3</td>
<td>0.4</td>
<td>3.0</td>
<td>3.3</td>
<td>5.6</td>
</tr>
<tr>
<td>$v_{sat}$ (cm/s)</td>
<td>$1.0 \times 10^7$</td>
<td>$1.0 \times 10^7$</td>
<td>$2.0 \times 10^7$</td>
<td>$2.5 \times 10^7$</td>
<td>$2.7 \times 10^7$</td>
</tr>
<tr>
<td>$\mu_n$ (cm$^2$/Vs)</td>
<td>1350</td>
<td>8500</td>
<td>700</td>
<td>1200 (Bulk)</td>
<td>2000 (2DEG)</td>
</tr>
<tr>
<td>$\Theta$ (W/cmK)</td>
<td>1.5</td>
<td>0.43</td>
<td>3.3~4.5</td>
<td>1.3</td>
<td>20</td>
</tr>
<tr>
<td>$JM = \frac{E_{br} v_{sat}}{2\pi}$</td>
<td>1</td>
<td>2.7</td>
<td>20</td>
<td>27.5</td>
<td>50</td>
</tr>
</tbody>
</table>
Several different materials such as Si/SiGe, GaAs, SiC, and GaN have been used for development of high-performance microwave/RF transistors and amplifiers. Especially, wide band gap GaN-based materials have superior properties as follows. Breakdown field is higher by one order of magnitude than Si and GaAs, AlGaN/GaN heterostructures have a high density of 2-dimensional electron gas (2DEG) due to strong piezoelectric effects, and the theoretical maximum electron drift velocity of GaN reaches 2.9×10^7 cm/s at a very high field of 140 kV/cm because of a high optical phonon energy [11]. Johnson’s figure-of-merits [10] clearly show that wide-band gap GaN materials have superiority for high-power and high speed applications since they have high breakdown field and high saturation velocity compared with GaAs and Si semiconductors. AlGaN/GaN heterostructures achieve high carrier mobility/high carrier density and minimal impurity scattering compared to SiC material. Such superiorities of AlGaN/GaN HEMTs lead to power density several times higher than other commercially available devices. Thus, GaN-based materials have been considered to be excellent candidates to replace currently utilized GaAs and Si for microwave applications. In addition, there has been a continuous progress in GaN material growth/device fabrication technologies. Thanks to such improvements in GaN technologies, era of GaN-based HEMTs is expected to come in microwave/RF power applications.
However, critical issues including current dispersion and device reliability have limited AlGaN/GaN HEMTs for practical applications. Current dispersion due to trapping effects associated with these devices causes decrease in the actual output drain current and voltage swing at RF operations [12]. These traps are mostly related to crystalline imperfection induced during material growth and device processing: 1) Defects in the AlGaN/GaN heterostructures are due to lattice mismatch with foreign substrates such as SiC and sapphire, unintentional impurities, and compensation doping; 2) Device fabrication processing can impose thermal, physical, and chemical damage. In addition, the activity of traps changes under high power operation, degrading direct-current (DC)/radio frequency (RF) performance of AlGaN/GaN HEMTs. Thus, to minimize trapping effects through control of surface/interface states, development of advanced material growth/device fabrication process techniques and novel device structures has been one of key research themes in AlGaN/GaN HEMTs for high power, high speed, and high temperature applications. For this reason, a practical model for trap characterization should be developed to evaluate newly-introduced techniques. Even though there have been remarkable improvements in growth/device fabrication technologies, trapping effects in AlGaN/GaN HEMTs cannot be removed perfectly, indicating that an accurate HEMT model including trapping effects is still needed. Therefore, it is important to perform trap study on device stability/reliability to develop a
practical and precise HEMT model with consideration of trapping effects for achievement of high performance GaN-based HEMTs for commercial or military applications. The efforts of this Ph.D research are devoted to understand trapping/detrapping phenomena in AlGaN/GaN heterostructures, interpret electron trapping effects on HEMT performance, and develop qualitative/quantitative methods for trap characterization.

1.2 Current dispersion as a limiting factor in AlGaN/GaN HEMTs for high-power/high-speed applications

1.2.1 Current dispersion in AlGaN/GaN HEMTs

Currently, measured AlGaN/GaN performances haven’t come close to the theoretical expectation based on the superiority of GaN-based material properties. One of the main reasons is trapping effects in AlGaN/GaN HEMTs during HEMT operation, causing current dispersion between DC/RF or DC/pulsed I–V characteristics. In general, trapping effects mean electron capturing by traps somewhere in AlGaN/GaN heterostructures. The captured electrons reduce the sheet electron density in the channel to keep the overall charge neutrality, leading to drain current dispersion. The dispersion is a
phenomenon that drain current ($I_D$) in pulsed or RF current-voltage ($I$–$V$) characteristics becomes lower than $I_D$ in DC $I$–$V$'s as shown in Figure 1.2 [13].

Figure 1.2 A sketch of FET $I$–$V$ characteristics before (full curves) and after (dotted curves) current collapse at a quiescent bias point (Q). The maximum attainable device output power is approximately proportional to the area of the broken rectangles, before and after collapse, respectively [13].

Figure 1.2 shows schematic $I$–$V$ characteristics before and after current collapse to show trapping effects on output power performance in FETs. The maximum voltage
swing ($\Delta V$) is the difference between breakdown voltage ($V_{br}$) and knee voltage ($V_{knee}$) and the maximum current swing ($\Delta I$) is given by $I_{max}$. The maximum output power is expressed as the following equation [13, 14],

$$P = \frac{(\Delta V \times \Delta I)}{8}.$$ 

As shown in Figure 1.2, available maximum current, knee voltage and breakdown voltage are critical factors for determining output power density of FETs. Current dispersion due to trapping effects reduces the maximum current and changes the knee voltage. Surface trap states acting as the most likely origin of the trapping effects are very closely related to breakdown performance in AlGaN/GaN HEMTs since gate-leakage/breakdown mechanism is considered to be trap-associated process [15-18]. In other words, breakdown voltage in AlGaN/GaN devices depends on energy level and density of active traps [16]. However, electron trapping mechanism is still unclear while the resultant HEMT power performance degradation has been clearly observed. Thus, review of currently reported trapping and breakdown mechanism is important for building up theoretical and experimental knowledge about traps for development of noble growth/device fabrication techniques to achieve high-power performance AlGaN/GaN HEMTs.
1.2.2 Trapping mechanism: surface/bulk electron trapping

In general, electron trapping in AlGaN/GaN HEMTs can occur at different locations such as metal/AlGaN interface, the ungated AlGaN surface near the gate edge, AlGaN/GaN interface, and the buffer GaN layer during HEMT operation. Most of reported models to explain the current dispersion are classified into two categories: surface trapping [14, 19-23] and bulk trapping [13, 20, 24-27] depending on the position of traps.

Surface trapping

The surface trapping model, as a widely-accepted theory, has been known to be related to surface donor-like states. A proposal about the origin of electrons in the two dimensional electron gas (2DEG) at AlGaN/GaN interface, suggested by Ibbetson et al. [28], is helpful to understand the surface trapping.

Figure 1.3 shows a cross-sectional conduction band diagram in AlGaN/GaN HEMTs to display distribution of various space charge [28]. Conduction band offset between AlGaN and GaN produces two-dimensional well in GaN buffer near the AlGaN/GaN interface. The piezoelectricity in AlGaN/GaN systems creates positive charge in one side of strained AlGaN layer near the AlGaN/GaN interface, and negative
charge in the other side of the AlGaN near the surface, resulting in electric field across the AlGaN barrier.

Figure 1.3 Schematic conduction band diagram in the AlGaN/GaN showing the various space charge components [28]

“Surface donor model” by Ibbetson et al. is based on the following statements: 1) their net contribution of polarization-induced charges to total space charge distribution is zero
since the amounts of both positive and negative polarization charges are equal. 2) Contribution of any donor states in GaN buffer is also neglected. This is based on the fact that 2DEG confinement cannot be explained if fixed positive charges are left (i.e., depletion). Note that GaN buffer layer is unintentionally n-type doped and some electrons thermally generated from the donors (not from valence band because of wide band gap) may be contributed to 2DEG. Again, the thermal generation portion is considered to be zero in the surface-donor model. In fact, it has been experimentally demonstrated that various surface treatments affect 2DEG density in AlGaN/GaN HEMT structures [21, 29-32], indicating that electrons in 2DEG are directly related to surface states. 3) Owing to the strong polarization field, surface states donate electrons to the well to form 2DEG in the channel and positively ionized charges are left on the surface. 4) Finally, the 2DEG density is equal to the sum of the number of ionized dopants in AlGaN layer and the number of positive surface states. Even undoped AlGaN/GaN heterostructures have \( \sim 10^{13} \, \text{cm}^{-2} \) of sheet charge density in the channel [33, 34]. Thus, surface states should be considered as one of the most important factors to understand the physics in AlGaN/GaN HEMTs. The role and mechanism of surface electron trapping in drain current collapse and surface trapping mechanisms are reviewed as follows.

In AlGaN/GaN HEMTs, as normally-on transistors, drain current decreases as gate bias increases negatively. At a certain negative gate voltage, drain current becomes
zero, ideally, over any drain voltage. This is because the negative bias on gate (i.e., pinch-off voltage) fully depletes electrons in the channel under the gate. However, the conventional principle cannot explain the current dispersion. This is because electron trapping at Schottky gate/AlGaN surface shifts threshold voltage ($V_T$) of AlGaN/GaN HEMTs but drain current in pulsed $I–V$s with pinch-off quiescent bias (QB) is still lower at a higher $V_{GS}$ to compensate $V_T$ shift than that in DC $I–V$s. For this reason, “virtual gate (VG)” concept proposed by Vetry et al. is reasonable to explain current dispersion due to surface trapping on the ungated surface between gate and drain contacts under a positive drain bias and pinch-off gate bias shown in Figure 1.4 [14, 21].

![Figure 1.4 Model of the device showing the location of the virtual gate and schematic representation of the device including the virtual gate [14]](image-url)
The VG can be formed with a group of electrons captured by surface states, if sufficiently high negative voltage (not necessarily pinch-off bias) is applied on the gate. It has been frequently reported in AlGaN/GaN heterostructures that a major electron trapping mechanism on AlGaN surface is tunneling of electrons from the gate to the ungated AlGaN surface [16, 18, 19, 21-23, 26, 35-37]. It could be also the combination of tunneling and surface hopping [38]. As a result of electron injection from the gate, the unintentional negative gate is located near the gate edge between drain and gate contacts and induce electron depletion under the VG, resulting in extension of depletion region as shown in Figure 1.4. Vetury et al. [14] suggested that after the negative gate voltage is removed, a certain time to emit those captured electrons is needed because the VG bias still exists until VG diminishes to steady-state potential at a given $V_{DS}$. The remaining VG before steady-state potential reduces the sheet electron density in the channel. That is why the drain current is decreased in the pulsed $I-V$ is as shown in Figure 1.2. This is also called a delayed response of drain current to the gate bias variation from off-state to on-state, or “gate lag.” Koley et al. also observed slow transients in both drain current and surface potential profile near drain-side gate edge as shown in Figure 1.5 and 1.6 [35]. The observation that the transient of drain current follows that of the surface potential near the drain-side edge supports the virtual gate concept and electron trapping on the ungated AlGaN surface near the gate edge. Thus, it is considered that electron trapping
on the ungated AlGaN surface is clearly one of the main reasons for current dispersion in AlGaN/GaN HEMTs.

Figure 1.5 Transient characteristics of drain current and surface potential in AlGaN/GaN HEMTs at \((V_{DS}, V_{GS}) = (1 \text{ V}, 0\text{V})\) after the HEMT is stressed at \((V_{DSQ}, V_{GSQ}) = (20 \text{ V}, -12 \text{ V})\) for 2 minutes. Note that the Kelvin probe tip is placed \(~0.4~0.5 \, \mu\text{m}\) away from the gate foot [35].
Figure 1.6 Variation of surface potential with distance from the edge of the gate at different intervals of time. After the biases is pulsed from \((V_{DSQ}, V_{GSQ})=(20\,\text{V}, -12\,\text{V})\) to \((V_{DS}, V_{GS}) = (0\,\text{V}, 0\,\text{V})\). The inset shows a list of the intervals [35].

Mantra et al investigated the field-dependence of active traps to interpret trapping/detrapping in the barrier near the AlGaN surface [19, 22, 23]. Figure 1.7 shows energy band diagram of a trapping center in the presence of electric field together with three possible mechanisms of electron emission [23].
Figure 1.7 Schematic energy diagram of the trapping center in the presence of the electric field. Three possible mechanism of emission from the trap: Poole-Frenkel (PF) emission due to thermal ionization, phonon-assisted tunneling (PAT), and direct tunneling (DT) [23].

First, trapped electrons are thermally ionized over the lowered barrier (Poole-Frenkel effect) on the conduction band and drift down to the channel. Second, combination of thermal energy and electric field can lead to the phonon-assisted tunneling (PAT). Finally, direct tunneling can happen when the electric field in the barrier is high enough compared with trap energy level \(E_T\). If the emission process of trapped charge in AlGaN barrier follows the Poole-Frenkel electron emission among three different-type emissions, the emission rate \(e\) should be proportional to \(\exp(\sqrt{F})\) or \(\exp(\alpha\sqrt{V_D})\) where \(F\) is electric

16
field, $V_D$ is applied voltage between gate and drain, and $\alpha$ is a correlation constant between the applied voltage and the lowering of the trap potential. The relationship between emission rate and $V_D$ at $V_{GS} = 0$ V is derived from the combination of following three equations [23]. First, assuming that the emission is a thermally activated process, the emission rate from trap level can be expressed by the following Arrhenius equation:

$$e = AT^2 \exp\left(\frac{-E_i}{kT}\right)$$

Second, the barrier decrease ($\Delta \phi_{PF}$) due to the high electric field (PF effect) is proportional to the square root of the applied electric field ($F$) as follows:

$$\Delta \phi_{PF} = \left(\frac{q^3}{\pi \varepsilon}\right)^{1/2}\sqrt{F} = \beta \sqrt{F}$$

where $q$ is a unit of electron charge and $\varepsilon$ is the dielectric constant. Third, the ionization energy as a function of a field can be written as:

$$E_i(F) = E_i(0) - \beta \sqrt{F}$$

where $E_i(0) = E_T$ is the binding energy of the electron on the trap in the zero field. Finally, they deduced the field-dependent emission rate equation:

$$e(F) = e(0) \exp\left(\frac{\Delta \phi_{PF}}{kT}\right) = e(0) \exp\left(\beta \sqrt{V_D}\right)$$

Figure 1.8 shows the emission rate as a function of the square root of the applied voltage after a gate bias pulses up from $-3 \sim -5$ V to 0 V [23].
Figure 1.8 Emission rate as a function of the square root of the applied voltage \( (V_D) \) in different samples A, B, and C. The depth and the duration of the filling pulses for samples A, \( V_G = -3 \) V and \( \tau_p = 350 \) ns; B, \( V_G = -5 \) V and \( \tau_p = 1000 \) ns; and C, \( V_G = -4 \) V and \( \tau_p = 1000 \) ns [23].

More strictly, the field-dependent emission rate equation should include built-in potential due to polarization field in AlGaN/GaN barrier (\( \sim 10^6 \) V/cm). The emission rate can be rewritten as:

\[
e(F) = e(0) \exp\left(\beta \sqrt{V_D + V_{bi}}\right)
\]

where \( V_{bi} = (\phi_b - \Delta E_C + E_F)/d_{AlGaN} \) is the built-in field across AlGaN barrier, \( \phi_b \) is the barrier height at the AlGaN surface, \( \Delta E_C \) is conduction band offset between AlGaN and
GaN, and $E_{Fi}$ is the difference between Fermi level and GaN conduction band edge at the AlGaN/GaN interface. Thus, if $V_D >> V_{bi}$, their extracted zero-field emission rate can be close to $e(0) \exp(\beta \sqrt{V_{bi}})$ which is not really zero-field emission. Nevertheless, it is considered that Poole-Frenkel type emission is dominant for the trapped charge near the AlGaN surface. It is inferred that the trapped electrons stay near the AlGaN surface below a certain $V_{DS}$ (or $V_{GD}$), resulting in channel depletion and drain current collapse, until $V_{DS}$ is large enough for phonon-assisted field emission or direct field emission from the surface to the channel. Capture/emission mechanisms, leakage/breakdown mechanisms, and current dispersion in AlGaN/GaN HEMTs will be described in more details in Chapter 3, 4, and 5.

Bulk trapping

Electron trapping in GaN buffer has been considered to be one reason for current dispersion [13, 20, 25-27, 39] since Khan et al. reported drain current reduction after AlGaN/GaN HEMT operation at high drain as shown in Figure 1.9 (a) [24]. In fact, it is mentioned in Ref. [24] that the current collapse after the HEMT experiences high voltage ($V_{DS} < ~ 20$ V in Figure 1.9 (a) ) between source and drain is attributed to traps in AlGaN barrier when electrons in the 2DEG channel can have sufficient energy to be injected into AlGaN layer.
Figure 1.9 $I-V$ characteristics exhibiting current collapse in an AlGaN/GaN HEMT structure before and after the application of a high drain bias. (a) Ref. [24] and (b) Ref. [26]. Note that (i) in (a) and the dashed line in (b) are before the application of a high drain bias.

However, later on, this type of current collapse at high drain voltage has been considered to be attributed to injection and trapping of hot electrons in GaN buffer as shown in Figure 1.9 (b). This is because the similar behaviors have been observed in $I-V$ characteristics of GaN metal semiconductor field-effect-transistors (MESFETs) [40, 41]. Once hot electrons are captured by trapping centers in the buffer, channel is depleted and the drain current is reduced. The current dispersion is recovered at a higher drain voltage.
Note that trapping of hot electrons in AlGaN barrier can still not be completely ruled out. Binari et al. reviewed bulk trapping effects and characterization and identification of those bulk traps in AlGaN/GaN HEMTs and GaN MESFETs [13, 39]. From their review, it can be known that traps related to bulk trapping are deep and originated from compensation doping (carbon), which is used to make highly resistive or semi-insulating buffer. Measurements of drain lag as a delay response of drain current to \( V_{DS} \) change is one method to analyze current collapse due to trapping effects. Figure 1.10 (a) shows drain lag measurement results when the drain voltage is pulsed up from a low voltage value (10 ~100 mV) to 15 ~20 V and then returns to the low drain voltage at a fixed \( V_{GS} = 0 \) V [26], claiming that Device C in Figure 1.10 on an optimized wafer with resistive GaN buffer shows no drain lag. Devices fabricated on an non-optimized wafer show a huge drain lag (Device A on less conductive buffer) or show no drain lag but aren’t pinched off (Device B on more conductive buffer). To prevent the bulk trapping, Palacios et al. made an attempt to insert a very thin small bandgap material (InGaN) between 2DEG channel near AlGaN/GaN interface and GaN buffer for a higher back-barrier [6] and Wong et al. reported that passivated N-faced HEMTs with AlN-GaN spacer showed a better 2DEG-confinement [44]. In addition, there has been improvement in growth technology, so buffer trapping becomes less important than surface trapping.
However, buffer electron trapping can still not be neglected completed or since the trapped charge in GaN buffer can affect channel mobility near $V_T$ and can be conductive or be emitted at a very high $V_{DS}$.

Figure 1.10 Drain lag measurement in three AlGaN/GaN HEMTs where GaN buffers have different electrical properties. The drain current is normalized to the initial current ($I_{D1}$) at the low voltage. A and B are devices on the same wafer but B is fabricated on more conductive buffer region than A. C is a device on another wafer having resistive buffer ($10^5 \, \Omega \text{cm}$). A: typical response. B: Conductive buffer. C: Optimized buffer (high resistive). [26].
So far, surface and buffer electron trappings have been separately discussed as in most of the works on trapping effects described above. Although it is known that current dispersion and device performance degradation are caused by various traps in the AlGaN surface, AlGaN barrier, and the GaN buffer, the identity of traps is still questionable. Although the drain lag has been attributed to buffer traps [26], Meneghesso et al. demonstrated in the simulation that slow deceasing $I_D$ transient in another type of drain lag measurement results when the applied biases are pulsed up from $(V_{DS}, V_{GS}) = (0 \text{ V}, 0 \text{ V})$ to $(6 \text{ V}, 0 \text{ V})$ as show in Figure 1.11 is due to hole emission (or electron capture) at the surface [45]. In addition, a question arises whether surface or buffer trapping can be independently examined experimentally or whether both trappings affect AlGaN/GaN HEMT operation separately. By combining surface and buffer trapping, trapping mechanism and trapping effects on AlGaN/GaN HEMT operation will be discussed more in Chapter 5.
Figure 1.11 Measured $I_D(t)$ transient when the drain voltage is pulsed up from 0 V to 6 V at a fixed $V_{GS} = 0$ V [45]

1.3 Efforts to minimize trapping effects

GaN-based high electron mobility transistors (HEMTs) have great potential for high power and high frequency applications thanks to their inherent superior material nature as described above. However, current collapse raising critical issues such as power/speed performance as well as device reliability has to be solved in AlGaN/GaN HEMTs for practical applications. A major source of the current collapse is electrically active traps created mainly during growth due to the lattice mismatch between foreign
substrates such as sapphire and SiC and III-nitride epitaxial films, and during device processing. The unavoidable traps in the AlGaN/GaN heterostructures capture electrons, deplete 2DEG in the channel causing current dispersion between static and dynamic current-voltage (I–V) characteristics [13], and also affect breakdown voltage and gate leakage current [21, 38]. Thus, control of electrically active traps is an important issue in AlGaN/GaN high electron mobility transistors (HEMTs) for high power, high speed, and high temperature applications.

Many efforts for high performance AlGaN/GaN HEMTs have been made to suppress RF current dispersion and thermal/electrical stress-induced degradation, or/and to improve the breakdown voltage performance, which are directly related to modification of surface/interface states in AlGaN/GaN heterostructures: surface passivation, a thin AlN barrier layer in AlGaN/GaN interface, application of a field plate, and Si doping on GaN/AlGaN/GaN heterostructures, dielectric layer insertion, surface treatments with chemicals or plasma, and post-gate-annealing (PGA) [3-5, 16, 29-31, 46-56]. In addition, many researchers have investigated about the origin, location, and density of traps and reported various physical models of trapping mechanisms [13, 14, 19, 20, 22, 23, 27, 28, 35, 38, 57-65]. It has been reported that possible sources of surface states in GaN-based materials are electrically active states at threading dislocations (TDs), and nitrogen vacancies (V_N) and oxygen impurities as shallow surface donors [59-63, 65].
TDs have been mostly considered to be negatively charged [59, 65], though positively charged states at TDs were also reported [62]. Hsu et al. suggested that the electrical behavior of dislocations depends on growth conditions and screw and mixed dislocations introduce excess reverse leakage current in GaN Schotty diodes [63]. V_N and Oxygen impurities as shallow surface donors have also been reported to cause gate leakage current [60, 61]. Although it has been suggested that various traps are the origin of current dispersion and device performance degradation, the identity of traps is still questionable.

Among various techniques to engineer electrically active surface states on device performance mentioned above, a popular way is surface passivation with dielectrics such as Si_3N_4 and oxide [14, 21, 29, 30, 64, 66-68]. Some groups have reported that surface passivation reduces electron trapping near the AlGaN surface [29, 66, 67]. The passivation of surface traps has generally meant removal of the trap states to prevent charge trapping causing the current dispersion as Figure 1.12 [29]. However, this explanation can be contradictory to surface donor theory by raising a question of trap sources as well as 2DEG source. Drain current level increase after passivation indicates that 2DEG density increases, and net surface charge and net AlGaN/GaN interface charge become less negative and less positive, respectively. So, several groups suggested that the improved current after passivation can be attributed to increase in positive charge at
dielectric/AlGaN interface [29, 30, 64, 67, 68]. Some more explanations for the passivation effects have also been proposed. First, the passivation process increase density of surface states (i.e., donor-likely states). Second, the passivation layers bury the traps to become inaccessible to electrons from the gate [14]. Third, the passivation layer reduces edge electric field near the gate edge, leading to minimize electron injection from the gate to AlGaN surface [20]. This suppression of the (peak) electric field near the drain-side gate edge is more dominant in field-plate HEMTs, resulting in reduced electron trapping on the AlGaN surface near the drain-side gate edge and increased breakdown voltage while it reduces the gain due to additional gate-drain capacitance [5, 69].

Figure 1.12 Gate lag measurement on unpassivated [(a)] and MgO passivated [(b)] AlGaN/GaN HEMTs. VG is switched from -5 V to 0 V [29]
Various surface treatments affect electrical properties of AlGaN/GaN heterostructures since the AlGaN surface is very sensitive to environments. Some groups presented that surface treatment with NH$_3$ and O$_2$ plasmas before passivation reduced current dispersion while the improvement of HEMT performance is not as much as that of passivation process only [31]. However, it is hard to draw any consistent conclusions since many reports about surface treatment effects have been based on DC measurements [70], and surface treatment effects vary with processing conditions and wafer quality [31, 56, 71, 72].

Insertion of a thin AlN interfacial layer between AlGaN barrier and GaN buffer improves HEMT performance since the AlN layer reduces alloy-disorder scattering at the interface, resulting in improved carrier mobility [46, 47], and decreased current collapse. It is suggested that the AlN interfacial layer induces a minimal transfer of channel electron to the AlGaN barrier [46]. Higashiwaki et al. reported the record $f_T$ of 190 GHz at $(V_{DS}, V_{GS}) = (4 \text{ V}, -3.8 \text{ V})$ and $f_{max}$ of 251 GHz at $(V_{DS}, V_{GS}) = (10 \text{ V}, -3.2 \text{ V})$ by using the combination of a thin and high-Al-concentration AlGaN barrier, catalytic chemical vapor deposition (Cat-CVD) SiN layer, and a very short gate length of 60 nm. This improvement is attributed to the effective plasma-free Cat-CVD SiN for isolation between the channel and the gate, increased 2DEG density due to high Al concentration barrier, less mobility degradation by the AlN interfacial layer, and a high aspect ratio of
gate length to barrier thickness for suppressing short channel effects. However, it seems that applying higher $V_{DS}$ is restricted for those HEMTs, resulting in limitation on high output power density.

Our group demonstrated that PGA process can be considered a simple way to manufacture high performance GaN-based HEMTs as we previously reported improvements in DC, RF and power performance of the AlGaN/GaN HEMTs after PGA [54]. The enhancement of HEMT performance by PGA was suggested to be related to change in the trap activity near metal/AlGaN interface [16, 17, 54]. In Chapter 3 and 4, PGA effects on HEMT performance and trapping/detrapping mechanism, and trapping effects on HEMT performance will be discussed in details. PGA study gives us insights in qualitatively understanding trapping effects in AlGaN/GaN HEMTs and provides us a helpful hint for development of quantitative trap characterization methodology, which will be presented in Chapter 5.

Device breakdown performance in AlGaN/GaN HEMTs is also closely related to active traps in AlGaN/GaN Heterostructures. These traps have been considered to act as a path for gate leakage current, hence have a large impact on device breakdown performance [16, 18, 38, 73]. Therefore, understanding and control of trap-related effects are also critical to fabrication of high-breakdown-voltage HEMTs for high power applications. For this reason, efforts have been made to understand breakdown
mechanism. Several leakage current mechanisms in GaN, AlGaN, and AlGaN/GaN Schottky contacts have been reported [15, 16, 18, 74-76]. Hashizume et al. suggested a surface barrier thinning model [15, 76] that high density of donors, existing very shallowly near the AlGaN or GaN surface, cause barrier thinning and enhance tunneling process. Alternatively, Miller et al.[74] and Karmalkar et al.[18] proposed trap-assisted tunneling where traps are involved in electron trapping and emission, leading to leakage current through Schottky barrier. Generally, AlGaN/GaN HEMTs with a field plate, gate dielectrics, and PGA processes have showed improved gate leakage/breakdown voltage performance, while in some cases surface passivation decreased breakdown voltage [66]. One should note that trapping effects on breakdown performance is not corresponding to current collapse due to electron trappings. For example, some HEMTs with severe current dispersion exhibit a very high breakdown voltage [16] in which case energy levels of active traps responsible for the current collapse are deep. For achieving high-power and high-speed performance at the same time, AlGaN/GaN HEMTs must exhibit high breakdown voltage as well as high switching speed as Zhang et al. mentioned [21] in development of novel device process techniques and advanced heterostructure layer designs for engineering surface/interface states as in field plate HEMTs. In other words, the newly-introduced techniques have to suppress electron injection from the gate and also modify trap energy levels to be shallow since surface traps are considered to be
avoidable based on surface donor model (positively-charged donor-likely states). Effects of deep and shallow level traps on HEMT performance will be discussed in Chapter 3 to 5.

1.4 AlGaN/GaN HEMT operation and electron transport

1.4.1 Basic theory of GaN HEMT operation

The principle of AlGaN/GaN HEMTs is very similar to that of any other-type FETs. The HEMTs have three terminal electrodes such as source, drain, and gate contact as shown in Figure 1.13. Source/drain contacts are ohmic and electrically connected to the 2DEG channel but the gate contact is electrically separated from the channel by AlGaN barrier acting as a dielectric layer like SiO₂ layer of Si metal-oxide-semiconductor Field-effect-transistors (MOSFETs). Electrons are supplied from source contact and flow to drain contact when positive voltage is applied to drain contact with respect to source contact \((V_{DS})\). The amount of the flowing electrons is controlled by applied voltage of gate contact (i.e., \(V_{GS}\)).
Figure 1.13 Typical AlGaN/GaN HEMTs structures having 2DEG channel in unintentionally-doped (UID) GaN buffer near AlGaN/GaN interface.

Figure 1.14 shows energy band diagram of AlGaN/GaN HEMTs with Schottky metal gate vertically from Schottky metal to GaN buffer. Since AlGaN/GaN Heterostructures has spontaneous and piezoelectric polarization effects of strained AlGaN barrier and GaN buffer, the charge balance can be expressed as in Eq. (1−1) based on the surface donor model [28, 77].

\[
|Q_{-\text{Net}}| = |\sigma_{\text{Polar}}^- + \sigma_{\text{Surface}}^+| = |Q_{+\text{Net}}^+| = |\sigma_{\text{Polar}}^+ + qn_S| \quad (1-1)
\]

where \(Q_{-\text{Net}}\) and \(Q_{+\text{Net}}\) are net charges at the AlGaN surface and AlGaN/GaN interface, respectively, and \(\sigma_{\text{Polar}}^-\) and \(\sigma_{\text{Polar}}^+\) are equal polarization charges at the surface and the
interface, respectively, and \( \sigma_{\text{Surface}}^+ \) is positively ionized donor-likely states at the AlGaN surface and a corresponding amount of \( qn_S \) is the density of two-dimensional electron gas (2DEG) in the channel.

\[
qV_{bi} = q\phi_b - (\Delta E_C - E_{F0})
\]

Figure 1.14 Schematic conduction energy band diagram of Schottky contact/AlGaN/GaN HEMTs showing charge balance across AlGaN barrier.

\[
Q_{\text{Net}} = Q_{\text{Net}}^+ - qn_S = C_{\text{AlGaN}}V_{bi}
\]
Note that total polarization charge at AlGaN/GaN interface ($\sigma_{\text{Polar}}^+$) is expressed as [78]:

$$\sigma_{\text{Polar}}^+ = \sigma_{\text{AlGaN}} - \sigma_{\text{GaN}} = (P_{SP} + P_{PE})_{\text{AlGaN barrier}} - (P_{SP})_{\text{GaN buffer}}$$  \hspace{1cm} (1-2)

where $\sigma_{\text{AlGaN}} = (P_{SP} + P_{PE})_{\text{AlGaN barrier}}$ is the sum of spontaneous and piezoelectric polarizations of strained AlGaN top layer and $\sigma_{\text{GaN}} = (P_{SP})_{\text{GaN buffer}}$ is spontaneous polarization charge in GaN buffer. For Ga-faced polarity in which case polarization in both AlGaN and GaN points toward the substrates, $\sigma_{\text{Polar}}^+$ is positive at AlGaN/GaN interface due to higher polarization (so, higher $\sigma_{\text{AlGaN}}$) in AlGaN than in GaN buffer [78-80]. Ambascher et al. investigated theoretical and experimental carrier concentration of 2DEG at various Al concentrations in both Ga– and N–faced AlGaN/GaN heterostructures [78]. The following expressions of physical properties as a function of Al concentration ($x$) in AlGaN/GaN heterostructures are excerpted from Ref. [78].

**Lattice constant:**

$$a(x) = (-0.077x + 3.189) \times 10^{-10} \text{ m}$$  \hspace{1cm} (1-3)

**Elastic constant:**

$$C_{13}(x) = (5x + 103) \text{ GPa} \text{ and } C_{33}(x) = (-32x + 405) \text{ GPa}$$  \hspace{1cm} (1-4)

**Piezoelectric constant:**

$$e_{31}(x) = (-0.11x - 0.49) \text{ C/m}^2 \text{ and } e_{33}(x) = (0.73x + 0.73) \text{ C/m}^2$$  \hspace{1cm} (1-5)

**Spontaneous polarization:**

$$P_{SP} = (-0.052x - 0.029) \text{ C/m}^2$$  \hspace{1cm} (1-6)
Note that those relationships as a function of Al fraction \( x \) above are based on linear interpolation between physical properties of GaN and AlN. By combining Eq. (1–2) to (1–6), the general expression of polarization charges (\( \sigma_{\text{Polar}}^− \) and \( \sigma_{\text{Polar}}^+ \)) for both Ga– and N–faced AlGaN/GaN heterostructures is deduced as:

\[
\begin{align*}
|\sigma(x)| &= \left| 2 \frac{a(0) - a(x)}{a(x)} \left( e_{31}(x) - e_{33}(x) \frac{C_{13}(x)}{C_{33}(x)} \right) + P_{SP}(x) - P_{SP}(0) \right| \\
&= \left[ \frac{\varepsilon_0 \varepsilon(x)}{d_{\text{AlGaN}}} \frac{\Delta \phi_m}{q} \right] \left[ \phi_b - \Delta E_C(x) + E_F(x) \right] \\
&\equiv \left[ \frac{\varepsilon_0 \varepsilon(x)}{d_{\text{AlGaN}}} \frac{\Delta \phi_m}{q} \right] \left[ \phi_b - \Delta E_C(x) + E_F(x) \right] \\
&= \left[ \frac{\varepsilon_0 \varepsilon(x)}{d_{\text{AlGaN}}} \frac{\Delta \phi_m}{q} \right] \left[ \phi_b - \Delta E_C(x) + E_F(x) \right] \\
&\equiv \left[ \frac{\varepsilon_0 \varepsilon(x)}{d_{\text{AlGaN}}} \frac{\Delta \phi_m}{q} \right] \left[ \phi_b - \Delta E_C(x) + E_F(x) \right]
\end{align*}
\] (1–7)

Using Eq.(1–7), the theoretical polarization charge for our Al\(_{0.3}\)Ga\(_{0.7}\)N/GaN wafer is calculated to be \( \sigma(x = 0.3)/q = \sigma_{\text{Polar}}^+ / q \approx 1.7 \times 10^{13} \text{ cm}^{-2} \). The maximum sheet carrier density at AlGaN/GaN interface for undoped heterostructures is written as [81]:

\[
n_S(x) = \frac{\sigma_{\text{Polar}}(x)}{q} = \frac{\varepsilon_0 \varepsilon(x)}{d_{\text{AlGaN}}} \frac{\Delta \phi_m}{q} \left[ \phi_b - \Delta E_C(x) + E_F(x) \right]
\] (1–8)

where dielectric constant \( \varepsilon(x) = -0.5x + 9.5 \), Schottky barrier \( \phi_b = (1.3x + 0.84) \text{ eV} \) [82], the Fermi level with respect to the GaN conduction band edge energy at AlGaN/GaN interface \( E_F(x) = E_0(x) + \pi(h^2n_S(x)/m^*)(x) \) [78], the ground subband level of the 2DEG \( E_0(x) = \left( \frac{9 \pi h^2}{8 \varepsilon_0 \sqrt{8m^*(x)}} \right) \frac{n_S(x)}{\varepsilon(x)} \) [78], the band offset \( \Delta E_C = 0.7 \left[ E_G(x) - E_G(0) \right] \) [83, 84], AlGaN band gap \( E_G(x) = xE_{G,\text{AlN}} + (1 - x)E_{G,\text{GaN}} - bx(1 - x) \text{ eV} \), \( E_{G,\text{AlN}} = 6.13 \text{ eV} \), \( E_{G,\text{GaN}} = 3.42 \text{ eV} \), and \( b \) is a band bowing parameter [85]. Electron effective mass \( m^*(x) \) can be estimated by the linear interpolation between \( m_{\text{AlN}}^* = 0.48m_e \) and
\( m_{\text{GaN}}^* = 0.2m_e[86] \), so \( m_{\text{AlGaN}}^*(x) = (0.28x + 0.2)m_e \). One should note that the expression of Schottky barrier height above was deduced by linear extrapolation between the barrier heights of Ni/bulk GaN and Ni/bulk Al_{0.15}Ga_{0.95}N diodes, so it is not guaranteed that the accuracy is good for Schottky metal/AlGaN/GaN diodes as for the bulk materials. Figure 1.15 shows theoretical sheet carrier concentration of the 2DEG at Ga-faced AlGaN/GaN interface and at N-faced GaN/AlGaN interface for different AlGaN barrier thickness using constant \( m_{\text{AlGaN}}^* \approx 0.22m_e[78] \) and \( b = 1 \text{ eV} \).

Figure 1.15 Theoretical carrier concentration of 2DEG channel near Ga-faced AlGaN/GaN or N-faced GaN/AlGaN interfaces for different AlGaN barrier thickness. Schematic conduction energy band diagram of Schottky contact/AlGaN/GaN HEMTs showing charge balance across AlGaN barrier. [78].
Based on Eq.(1−8) for 2DEG density, the threshold voltage \(V_T\) is given by

\[
V_T = -\frac{qn_S(x)}{C_{AlGaN}} = -\left\{ \frac{\sigma_{Polar}(x)}{C_{AlGaN}} - \frac{1}{q} \left[ \phi_B - \Delta E_C(x) + E_{Fi}(x) \right] \right\} 
\]

(1−9)

where \(C_{AlGaN} = \varepsilon_0\varepsilon_{AlGaN}/d_{AlGaN}\). Once \(V_T\) is known for a given \(x\), we can calculate \(n_S\), \(\sigma_{Polar}\), \(\Delta E_C\), \(E_{Fi}\) and \(\phi_B\). For example, typical \(V_T\) for our HEMTs is \(-4\ V \sim -4.5\ V\) with \(x = 0.3\) and \(d_{AlGaN} = 23\ nm\), \(C_{AlGaN} = \sim 3.60 \times 10^{-7}\ F/cm^2\) and \(n_S = -V_TC_{AlGaN}/q = \sim 9.0 \times 10^{12}\) to \(~1.01 \times 10^{13}\ cm^2\), while the theoretical \(n_S\) using Eq. (1−8) is \(~1.4 \times 10^{13}\ cm^2\). Note that the theoretical \(C_{AlGaN}\) value above is very close to the measured one. As a result, there are large differences in \(\Delta E_C\), \(E_{Fi}\), and \(\phi_B\) values between theoretical and measured \(n_S\) values. Especially, 3.06 eV of \(\phi_B\) estimated from our measurements is much larger than 1.23 eV of the theoretical \(\phi_B\). This is most likely because the actual \(\sigma_{polar}/q\) value is much lower than the theoretical value (\(~1.68 \times 10^{13}\ cm^2\)). If actual \(\sigma_{polar}/q\) value is \(~1.18 \times 10^{13}\ cm^2\) (\(~70\%\) of the theoretical value), the estimated \(n_S\) is \(~1.01 \times 10^{13}\ cm^2\) and \(\phi_B\) is \(~0.82\ eV\), which are in a good agreement of the \(n_s\) value calculated with the measured \(V_T\) in Ni/AlGaN/GaN HEMTs and the measured barrier of Ni/AlGaN/GaN Schottky diodes. Nevertheless, those theoretical works give us fundamental insight into charge control model in AlGaN/GaN HEMTs. Based on Eq. (1−9), the charge control by the applied gate voltage can be express as:
\[ qn_s(V_{GC}) = C_{AlGaN}(V_{GC} - V_T) = C_{AlGaN} \left\{ V_{GC} + \left( \frac{\sigma_{Polar}}{C_{AlGaN}} - \frac{1}{q} [\phi_b - \Delta E_c + E_{F_s}] \right) \right\} \] (1-10)

where \( V_{GC} \) is the potential difference between the gate and channel \((V_G - V_C)\) and \( V_C \) is the position-dependent channel potential. \( I-V \) relationship of AlGaN/GaN HEMT in the linear region can be expressed as in Si MOSFETs including parasitic series resistances:

\[ I_D = \frac{\mu(E)C_{AlGaN}W_G}{L_{G,eff}} \left\{ V_{GT} - I_D R_S - 1/2 [V_{DS} - I_D (R_S + R_D)] - [V_{DS} - I_D (R_S + R_D)] \right\} \] (1-11)

where \( \mu(E) \) is field-dependent channel mobility for both vertical and lateral electric fields, \( W_G \) and \( L_{G,eff} \) are gate width and length, respectively, \( R_S \) and \( R_D \) are source- and drain-access parasitic series resistances, respectively, and \( V_{GT} = V_{GS} - V_T \). Once \( \mu(E) \) expression is known in AlGaN/GaN HEMTs with and without trapping effects, it will be feasible to analyze \( I-V \) characteristics for trapping-effect-associated device modeling. A proposed field-dependent velocity model in AlGaN/GaN HEMTs will be discussed in Chapter 5.

1.4.2 Electron transport in GaN-based materials

This sub-section illustrates electron transport in AlGaN/GaN HEMTs. Trend of electron drift velocity \((v_{drift})\) in GaN-based material heterostructures is not saturated even in a very high electric field (i.e., \( \sim 100 \text{kV/cm} \)) compared with Si and GaAs as shown in
Figure 1.16 [87] and starts to decrease at a critical field like GaAs due to inter-valley scattering. It has been difficult to apply conventional velocity field models in Si and GaAs to AlGaN/GaN HEMTs. O’Leary et al. reported an extensive review about electron transport in III-V nitride semiconductor based on three-valley Monte Carlo simulation method as illustrated in Figure 1.17 [11]. The following description is a short excerption of their review and a summary of some other papers to facilitate understanding of electron transport in GaN-based materials. Note that Ref. [11] is recommended for more detailed information about electron transport in III-V nitride semiconductors.

![Electron drift velocity characteristics as a function of electric field for various semiconductors](image)

Figure 1.16 Electron drift velocity characteristics as a function of electric field for various semiconductors [87].
Figure 1.17 Three-valley model for the conduction electron band structures of bulk wurtzite GaN used for the Monte Carlo simulations of the electron transport [11].

**Bulk GaN**

For the simulation in Ref. [11] and other reports [88-90], mainly phonon scattering (i.e., polar optical, piezoelectric, and acoustic deformation potential scattering), defect scattering (i.e., ionized impurity scattering), and intervalley scattering are considered since it is found that carrier scattering (i.e., electron-electron scattering) cause a very little change in the simulation results. Especially, it is shown that polar optical
phonon scattering is a key mechanism to determine the electron transport in III-V nitride semiconductors. In addition, when electron energy is high enough beyond a certain electric field, electrons start to transfer from one valley with a lower effective electron mass \( (m^*) \) to another with a higher \( m^* \) as general in III-V compound semiconductors. This is called inter-valley scattering, responsible for the negative differential mobility or drift velocity. Figure 1.18 shows steady-state electron velocity characteristics of GaN at 300 K, obtained from Monte Carlo simulation [11].

![Figure 1.18 Electron velocity characteristics as a function of electric field of bulk wurtzite GaN [11].](image-url)
Initially, $v_{\text{drift}}$ gradually increases as the applied field increases and then reaches a theoretical maximum $v_{\text{drift}}$ of $\sim 2.9 \times 10^7$ cm/s at $\sim 140$ kV/cm. Further increase of the electric field makes electrons having enough energy to transfer to the upper valleys, leading to decrease in $v_{\text{drift}}$, corresponding to the negative differential mobility region. Finally, $v_{\text{drift}}$ of becomes saturated to $1.4 \times 10^7$ cm/s for a very high electric field. They also examined the average electron energy with respect to the applied electric field, finding that the dominant energy loss mechanism below $\sim 100$ kV/cm is polar optical phonon scattering since the other types of scatterings as elastic scatterings (i.e., ionized impurity scattering, piezoelectric scattering, and acoustic deformation potential scattering) do not play any roles in the energy loss. Beyond the critical field ($\sim 100$ kV/cm), the polar optical phonon scattering cannot cause the electron energy loss and the inter-valley scattering starts to act as a dominant scattering mechanism. Eventually, at a certain high electric field, the number of electrons at each valley is saturated, and $v_{\text{drift}}$ stops decreasing and also reach saturation. Foutz et al. reported simulation results about transient electron transport of III-V nitrides. Transient velocity-characteristics of GaN as a function of distance across which various electric fields are applied are shown in Figure 1.19 [89], indicating that average electron velocity below 140 kV/cm quickly reach a steady-state velocity without any noticeable velocity overshoot while, above 140 kV/cm, significant overshoot is shown in a shorter distance region and the velocity is closer to
steady-state velocity in a longer distance region. Two important features of transient velocity characteristics in GaN are: 1) 140 kV/cm is a critical field as an onset of overshoot velocity and 2) there is negligible overshoot and steady-state velocity beyond ~0.2 μm distance.

Figure 1.19 Simulated average electron velocity with the distance where electric field is applied at different electric fields for bulk wurtzite GaN. The average electron velocity is calculated from a plot of the transient velocity with time at a specific field by assuming an initial zero field electron distribution, a crystal temperature of 300 K, and $N_d = 10^{17}$ cm$^{-3}$ [89].
Warack et al. reported a measured peak electron velocity of $1.9 \times 10^7$ cm/s at $\sim 224$ kV/cm without further noticeable decrease in $v_{\text{drift}}$ at a higher electric field [91], suggesting that a large defect density in GaN and a much lower inter-valley separation energy (0.34 eV) than one (i.e., $\sim 2$ eV) used in the simulations lead to the difference between theoretical and measured results in velocity characteristics [11, 91]. Bhapkar et al. showed that a high drift velocity of bulk GaN maintains at a higher temperature (i.e., peak $v_{\text{drift}} = 2 \times 10^7$ cm/s at 1000 K) compared with that of GaAs, indicating GaN based material is more suitable than GaAs (i.e., peak $v_{\text{drift}} = 1 \times 10^7$ cm/s at 500 K) for high temperature applications [90]. Thus, GaN-based materials is an excellent candidate for high power/temperature devices.

**AlGaN/GaN Heterostructures**

Similar approaches as in GaN bulk have been applied for the simulation of the electron transport in AlGaN/GaN heterostructures [90, 92-96]. However, according to Li et al., there are several additional issues in examining electron transport in AlGaN/GaN heterostructures unlike bulk GaN: 1) Large-polarization-induced effects; 2) interface roughness scattering; 3) screening effects due to high electron density; 4) degeneracy effects; 5) heterostructure geometry and Al mole fraction; 6) bias conditions for both lateral and vertical fields. Those issues are correlated with sheet carrier density and
interface electric field. For example, a higher polarization due to high Al concentration of AlGaN barrier induces higher sheet carrier density and higher interface electric field, resulting in increased screening effects and reduced electron mobility. In this sense, a high Al concentration causes the same effect as a high gate bias. The interface scattering is also dependent on a vertical field. So, both effects of the polarization and interface scattering can be combined with influence of a gate bias. They showed that, for a given Al fraction, effects of degeneracy and interface scattering are dominant at high gate voltage [92]. Yu et al. reported electron velocity characteristics as a function of electric field in AlGaN/GaN HEMTs with different Al fractions as shown in Figure 1.20 [94]. They claimed that a higher Al fraction induces a higher polarization field and sheet carrier density, and a larger band offset, leading to increased interface scattering as mentioned by Li et al [92]. It was also showed that as applied electric field increases, interface scattering becomes less important since at high electric field, electron transports in AlGaN/GaN heterostructures behave like those in bulk GaN or AlGaN while interface scattering mechanism is dominant in a low field region [94]. Some groups considered both deformation potential and piezoelectric scattering to be inelastic and also ignored any electron penetration into the AlGaN barrier [95, 96] to simulate field-dependent electron-velocity characteristics with hot-phonon effects, showing a good agreement
between experimental and theoretical drift velocity and current as a function of an applied electric field.

Figure 1.20 Simulated electron velocity as a function of electric field in AlGaN/GaN Heterostructures with different Al concentrations (15 %, 20%, and 30 %) [94].

So far, the measured electron velocity data are limited and there are huge discrepancies between experimental and theoretical values and between experimental values. For
example, for the same 15 % Al in AlGaN/GaN HEMTs, a measured $v_{\text{drift}}$ value (not saturated yet) in Ref. [96] is $1.1 \times 10^7$ cm/s at 100 kV/cm with 1 ns voltage pulse. Barker et al. reported the saturated $v_{\text{drift}}$ value of $1 \times 10^7$ cm/s at 150 kV/cm with 200 ns voltage pulse, and $3.7 \times 10^7$ cm/s at 140 kV/cm with 10 ns voltage pulse for different samples (25 % Al) [97]. Most likely, this is because heterostructure layer schemes, wafer/device qualities (contact resistance and defect density), and measurement set-ups and conditions are different from batch-to-batch and group-to-group, leading to non-consistency in experimental data. A model to extract the velocity from measured data may not be appropriate for AlGaN/GaN heterostructures. Thus, more experimental data as well as more accurate models in electron transport are required for drawing an acceptable conclusion for any typical behavior in field-dependent velocity characteristics. Practically, a measured saturation velocity can be determined from measured S-parameters (unit-gain cut-off frequency) [98, 99] once an effective gate length is known. Two-field model was introduced to explain electron drift velocity characteristics in AlGaN/GaN HEMTs with consideration of trapping effects [27, 100]. However, there has not been widely accepted field-dependent mobility or electron drift velocity in AlGaN/GaN HEMTs. Another way to estimate electron drift velocity (electron mobility) in AlGaN/GaN HEMTs is discussed in Chapter 5.
1.5 Research Objectives

Previous sub-chapters illustrated the potential and superiority of AlGaN/GaN HEMTs compared with Si and GaAs devices for high-power, high-speed, and high-temperature applications. Current collapse due to active traps has been one of the major research issues to solve for high performance AlGaN/GaN HEMTs and circuit applications. In fact, it is difficult to identify electrically active traps under device operation such as their position, spatial distribution and density, and origin. This is because there has been no method to separately identify these traps while the traps can exist not only near AlGaN surface, across AlGaN barrier, AlGaN/GaN interface, and GaN buffer. In addition, there has been no widely-accepted AlGaN/GaN HEMT model with quantitative trap characterization while many works about qualitative analysis of trap activity in AlGaN/GaN HEMTs have been reported. While there have been technological improvements to minimize trapping effects, the trap activity can’t be removed completely. Thus, an accurate HEMT model has to be devised for interpretation of existing trapping effects for development of both novel HEMT processing/material growth techniques and implementation of AlGaN/GaN HEMT-based circuits.

A primary goal of this Ph.D research is to develop a novel trap-involved HEMT model. At first, it is important to understand electron trapping/detrapping mechanism in
AlGaNa/GaN HEMTs to interpret the trapping effects on HEMT performances. PGA process affects device performance and trap activity in AlGaN/GaN HEMTs. Investigation about PGA effects using different annealing conditions gave us a better understanding on trapping/detrapping phenomena and a clue for qualitative and quantitative characterization of trap behavior. Electrical behavior of active trap states depends on measurement bias conditions for device testing and practical device operation conditions in real applications. Based on the understanding of trap behavior in AlGaN/GaN HEMTs, well-designed trap characterization schemes (i.e., either trap-free or trap-frozen operation conditions) are established for a more accurate HEMT model in the presence of the active traps during HEMT operation. Again, because of the difficulty in measuring accurate distribution of traps in energy and space, we have focused on development of a phenomenological model to interpret the trapping effects on AlGaN/GaN HEMT performance based on understanding of electron capture/emission mechanism. Using our proposed behavioral HEMT model, trapping effects on HEMT performances are characterized quantitatively in terms of device parameters such as threshold voltage ($V_T$), channel mobility ($\mu$), parasitic series resistance, effective gate length, etc. Details of the proposed model will be described in Chapter 5. These methods from the work to date on trap behavior of AlGaN/GaN HEMTs can be applicable for
development of novel material growth/device processing techniques to minimize the
trapping effects, device modeling and circuit applications.

The objectives of this Ph. D research are the following:

1) Investigate distinct electrical behavior of AlGaN/GaN HEMTs through study on PGA
effects using DC and pulsed I-V characterization under different pulse widths and
quiescent biases to understand electron capture/emission phenomena, interpret effects of
measurement conditions on trap activity, qualitatively analyze trapping effects on HEMT
performance, and evaluate PGA condition as a method for device processing monitoring.
2) Investigate identity of the active traps in various AlGaN/GaN HEMTs at different
levels of drain current dispersion between DC and pulsed $I-V$ characteristics based on
temperature-dependent drain current transients to correlate the extracted trap time
constants and activation energy levels with different current dispersion levels, and
examine electron trapping/detrapping mechanism and breakdown/gate current leakage
mechanism.
3) Investigate electrical behaviors of interface states at metal/AlGaN interface in
Ni/AlGaN/GaN Schottky diodes to discover PGA effects on Ni/AlGaN interface states by
comparing EBIC analysis results and electrical characteristics of Ni/AlGaN/GaN diodes.
4) Investigate if unintentional reaction on free AlGaN surface using XPS analyses during the PGA process. Unexpected oxidation on free AlGaN surface by PGA can prevent trapping of electrons injected from reversely-biased gate as the same role of the normal passivation layer.

5) Develop a simple behavioral HEMT model for trap characterization based on $I-V$ characteristics of AlGaN/GaN HEMTs to quantify trap activity in terms of device parameters and examine electron transport in AlGaN/GaN HEMTs for device processing monitoring, device modeling, and circuit application to achieve high-power, high-speed, and high-reliability AlGaN/GaN HEMTs.

All the efforts through this entire Ph.D research have been devoted to development of qualitative and quantitative methodology for trap characterization, establishment of a better understanding of device physics such as HEMT operation, electron trapping/detraping mechanism, electron transport, and so on in AlGaN/GaN HEMTs.

1.6 Organization

Chapter 2 illustrates procedures of AlGaN/GaN HEMT fabrication including optimization of dry-etching using ICP-RIE for mesa isolation and electron-beam lithography process.
In Chapter 3, characterization of trapping effects are described to understand effects of the post-gate annealing, using short drain current transient and static/dynamic current-voltage ($I-V$) measurements via study on PGA effects. It is also shown that the trap characterization and its interpretation can be applicable for examining other processing-induced effects on trap activity in AlGaN/GaN HEMTs.

Chapter 4 covers investigation on modification of electrical properties at Ni/AlGaN interface and compositional change of the free AlGaN surface before and after annealing. We present that change of electrically active states at Ni/AlGaN interface and the free AlGaN surface will be correlated with trap activity in AlGaN/GaN HEMTs with/without post-gate annealing (PGA).

In Chapter 5, quantitative characterization of trapping effects on AlGaN/GaN HEMTs are illustrated based on very short pulsed $I-V$ measurements using different quiescent biases (QBs) causing electron trapping over the AlGaN surface. Two methodologies for extraction of threshold voltage as well as other device parameters are proposed: 1) zero-drain-bias output conductance method (Model 1) and 2) low-drain-voltage field method (Model 2). First, short pulsed $I-V$ measurement condition is illustrated since our models are developed for analysis of trap-free and trap-frozen $I-V$ characteristics. Then, the following subsections cover current-voltage relationships in AlGaN/GaN HEMTs, basic concepts of both models, derivation of their model equations,
and discussion about their modeling results, electron trapping/detrapping mechanism, and electron transport in AlGaN/GaN HEMTs. Finally, the entire Ph.D research is summarized and future work for achievement of high performance HEMT is discussed in Chapter 6.
Chapter 2: AlGaN/GaN HEMT Fabrication

This chapter describes AlGaN/GaN heterostructures used in this dissertation, and HEMT fabrication procedure with optimization experiment for mesa isolation, ohmic metallization, and E-beam lithography. The standard HEMT processing procedure includes four lithography processes such as fiducial layer, mesa layer, ohmic contact layer, and Schottky contact layer. AlGaN/GaN HEMTs with \( \sim 0.2 \mu \text{m} \) Ni Schottky gate were fabricated for PGA study and HEMT models in Chapter 3 and 5. AlGaN/GaN diodes with large Schottky contacts were fabricated for EBIC study. Note that this chapter describes the standard process only for HEMTs and diodes and detailed device sample preparation for PGA study, EBIC/XPS studies, and HEMT models are illustrated in each following chapter.

2.1 AlGaN/GaN Heterostructures

For this dissertation about trap characterization, different AlGaN/GaN heterostructures were used. For PGA Study to examine trapping/detrapping phenomena and qualitative trap characterization, the AlGaN/GaN HEMT epilayer structure was grown by metal-organic chemical vapor deposition (MOCVD) on a SiC substrate. The
epilayers consist of 40 nm AlN nucleation layer, 3 µm of undoped GaN, and 20 nm undoped Al$_{0.3}$Ga$_{0.7}$N. For EBIC/XPS study in Chapter 4 to examine electrical properties of interface states at Ni/AlGaN interface and unintentional reaction of the free AlGaN surface, AlGaN/GaN heterostructure epilayers on a sapphire substrate grown by MOCVD consist of 40 nm AlN nucleation layer, 3 µm of undoped GaN, and 31 nm undoped Al$_{0.29}$Ga$_{0.71}$N. For development of HEMT model including trapping effects in Chapter 5, AlGaN/GaN heterostructures used consist of 23 nm Al$_{0.3}$Ga$_{0.7}$N and 2–3 µm GaN buffer with ~1 nm AlN interfacial layer grown by MOCVD on SiC substrates.

2.2 HEMT processing procedure

Before standard HEMT process is performed, AlGaN/GaN heterostructure samples have to be cleaned by degreasing process. The following fabrication processes are 1) formation of the fiducial layer, 2) mesa-isolation, 3) ohmic metallization, and 4) Schottky metal contact formation. Note that additional metal layer (i.e., overlay) is deposited for a better conduction smoother and surface roughness for all annealed contact pads, and for electrical connection between gate contact on the active area and Schottky contact pad on the etched area for gate bias application. The overlay process is not included since the process is the same as Schottky contact formation process using
photolithography or it can be done with Schottky contact formation process using e-beam lithography. Figure 2.1 shows the flow of standard HEMT process after formation of the fiducial layer.

2.2.1 Fiducial layer

Fiducial layer plays a role as a reference layer for the following lithography processes. For this layer, there is no alignment simply because this is the first layer. This layer provides various alignment marks to align the following photolithography and electron beam lithography processes. After patterning samples with photolithography, Ti/SiO₂/Ti/Au layer with thickness of 500/1200/300/2000 Å is deposited on open windows of the patterned samples and lift-off is performed. SiO₂ layer acts as a diffusion barrier when samples are annealed for ohmic metallization, so that the shape (edge) of the square mark is kept as sharp as possible for the following alignment after high temperature annealing process.
Figure 2.1 HEMT processing flow from mesa-isolation to Schottky gate formation
### 2.2.2 Mesa Isolation

Mesa isolation process by dry etching is performed to define active areas on samples. All the etched area is semi-insulating and the active areas are electrically isolated between each other. The dry etching technique used is inductively-coupled plasma reactive ion etching (ICP-RIE) method using chlorine-based plasma (BCl₃/Cl₂/Ar) and photoresist (PR) etch mask (AZ 5214 or Shipley 1811). After dry etching, the acetone is used to remove PR mask. The dry etching process generally induces plasma damage on the etched surface since high-density and high-energy plasma is used. To obtain the optimum dry-etching conditions in our ICP-RIE system, DC bias (or RF power) varied at a fixed ICP power since most of the plasma-induced damage is considered to be due to physical ion-bombardment. For this optimization experiment, flow rates of reacting gases chamber pressure are fixed as shown in Table 2.1.

<table>
<thead>
<tr>
<th>Condition</th>
<th>RF power (DC bias)</th>
<th>Etch rate</th>
<th>ICP power</th>
<th>Pressure</th>
<th>Flow rate of BCl₃/Ar/Cl₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>100 W (~260V)</td>
<td>75 nm/min</td>
<td></td>
<td>150 W</td>
<td>10 mtorr</td>
</tr>
<tr>
<td>B</td>
<td>60 W (~180 V)</td>
<td>60 nm/min</td>
<td></td>
<td></td>
<td>20/5/10 (sccm)</td>
</tr>
<tr>
<td>C</td>
<td>28 W (~100 V)</td>
<td>31 nm/min</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Note that BCl$_3$ enhances etch rate since it increases Cl radical density, and Ar with BCl$_3$ also increases etch rate of GaN and makes etch profiles relatively more anisotropic and smooth [101]. Figure 2.2 shows leakage currents at different RF powers between adjacent mesas after ohmic metallization. These mesa regions have to be electrically isolated against each other for a better device performance (i.e., breakdown voltage and pinch-off characteristics).

Figure 2.2 Leakage current at different RF power between adjacent mesa regions after ohmic metallization.
Figure 2.3 shows the etched surface and mesa edge of AlGaN/GaN HEMTs whose dry etching conditions are different: Figure 2.3 (a) and (b) are corresponding to condition A with RF power of 100 W (≈260 V DC bias) and condition C with RF power of 28 W (≈100 V DC bias), respectively, in Table 2.1.

Figure 2.3 Comparison of the dry-etch profiles between two different etch conditions. (a) is condition A with RF power: 100 W and (b) is condition C with RF: 28 W

A low RF power (or DC bias) leads to lower leakage current and less plasma damage. As a result, HEMTs with Condition A didn’t show any pinch-off performance but HEMTs
with Condition C have a reasonable pinch-off. However, we observed that drain leaky current is still high (~μA) even using Condition C and uniformity of leak current characteristics is not as good as we expected. For further suppression of the leakage current through the dry-etched area, we introduced post-oxygen plasma treatment as an additional process, expecting the same effect as the general passivation. To test effects of oxygen plasma treatment on leakage current, the same HEMTs with Condition A as shown in Figure 2.3 were used. The HEMTs with Condition A were treated with O₂ plasma while the active mesa regions were covered with PR mask during the post O₂ plasma treatment. O₂ plasma treatment conditions are similar to O₂ descum condition. Most of the HEMTs showed a lower drain leakage current at the same \( (V_{DS}, V_{GS}) \) than before the O₂ plasma treatment as shown in Figure 2.4. Although the leakage current cannot be completely removed, the test results indicate that O₂ plasma treatment is a simple and effective process for passivation of the plasma-induced damage. After further study of dry etching condition, the best dry etching process is found to be combination of low-DC bias dry etching and in-situ O₂ plasma treatment immediately after dry etching of mesa isolation, resulting in a very good pinch-off characteristics (i.e., less than a few nA at \( V_{DS} = 5 \text{ V} \) at \( V_{GS} \) near \( V_T \)). The optimum etching conditions with in situ oxygen plasma treatment after dry etching are listed in our ICP-RIE system lists in Table 2.2.
Figure 2.4 $I_D-V_{DS}$ characteristics of AlGaN/GaN HEMTs with Condition A before and after O₂ plasma treatments. The black-solid and red-dashed lines are corresponding to before and after O₂ plasma treatments. Note that Condition A is the dry etching condition with RF power of 100 W as shown in Table 2.1.

Table 2.2 Optimum dry-etching conditions for mesa isolation of AlGaN/GaN heterostructures using ICP-RIE system.

<table>
<thead>
<tr>
<th>1. Dry etching</th>
<th>Etching Gas (sccm)</th>
<th>Power</th>
<th>$P_{Set}$</th>
<th>Etch depth</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>BCl₃(20) /Ar(5)/Cl₂(10)</td>
<td>RF (DC bias)</td>
<td>ICP</td>
<td>10 mtorr</td>
</tr>
<tr>
<td></td>
<td></td>
<td>28 W (-100V)</td>
<td>150 W</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>2. In-situ plasma treatment</th>
<th>Gas (sccm)</th>
<th>Power</th>
<th>$P_{Set}$</th>
<th>Treatment time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>O₂ (50)</td>
<td>RF (DC bias)</td>
<td>zero</td>
<td>20 mtorr</td>
</tr>
</tbody>
</table>
2.2.3 Ohmic metallization

Ohmic metal scheme used in this study is multilayer Ti/Al/Mo/Au with thickness of 350/900/600/1000 Å. After ohmic metal regions are open by PL patterning using AZ 5214 PR (image reversal process), the multi-metal layers are deposited. Then, samples are annealed at 850 °C for 30 seconds in N₂ ambient using rapid thermal annealing (RTA) system. Ti is for a better adhesion and can be formed TiN on AlGaN surface, possibly leading to better conduction. Al is a kind of Nitrogen absorbing layer during annealing. Ohmic contact mechanism in AlGaN/GaN HEMTs is unclear but tunneling mechanism is the dominant conduction mechanism so far proposed via nitrogen vacancy-related surface donors in ohmic contact/AlGaN/GaN heterostructures [102-105]. It is reported that Ti and Al create nitrogen vacancies as shallow donors [102, 105, 106]. Mo is a diffusion barrier to prevent from mixing between Al and Au and laterally flowing Al and/or Al/Au mixed phase as low-melting materials during RTA causing a bad acuity of ohmic contact edge [106]. The top Au layer is for preventing from oxidizing Al. Four-point probe measurements of transfer length measurement (TLM) patterns are performed to determine contact resistance and specific contact resistivity. Figure 2.5 shows contact resistance and resistivity as a function of annealing temperature. The optimum temperature is 850~860 °C in our RTA system. Typical contact resistance and specific
contact resistivity are of 0.3~0.6 Ωmm and of 2~7 x 10^{-6} Ωcm^2 using RTA at 850 °C for 30 sec in N₂ ambient.

![Graph](image)

Figure 2.5 Typical Contact resistance and resistivity as a function of temperatures of TLM samples annealed for 30 sec in N₂ ambient. 850~850 °C is found to be optimum annealing temperature for our RTA system.

### 2.2.4 Schottky contact formation

Various Schottky metals with higher work functions such as Pt, Ni, Ir, and Pd have been used for Schottky gate contact in AlGaN/GaN HEMTs. Photolithography for
Schottky contact patterning is used for AlGaN/GaN Schottky diodes with large Schottky areas. For a large Schottky diodes and long-gate HEMTs, gate formation process is basically the same as ohmic metallization one except for annealing and metals to be deposited. On the other hand, E-beam lithography (EBL) is performed for sub-micron-long gate patterning using tri-layer e-beam resist (950k-PMMA/Co-polymer/50k-PMMA). Typical gate length in this study is \( \sim 0.2 \mu \text{m} \). T-shape gate as shown in Figure 2.1 and 2.3 is formed for both short gate length and low gate resistance/capacitance. Each resist layer is spincoated and baked at 200 °C for 2 min. Then, samples are e-beam-written with EBPG5000, developed with a 1:3 mixture of methyl isobuthyl ketone (MIBK) and isoprophyl alcohol (IPA) for 2 minutes, and dipped in IPA to stop the development. Figure 2.6 shows actual gate length as a function of dosage with 25 nm gate in the layout. To get \( \sim 200 \) nm gate length of the actual gate, 25 nm-long gate designed in the layout is used for e-beam writing, electron beam current and field is 100 pA and 100 kV, respectively, and dosage for gate footprint and sidelobe is \( \sim 1900 \mu \text{C/cm}^2 \) and 270 \( \mu \text{C/cm}^2 \). Next, Ni (\( \sim 20\text{nm} \)) and Au (\( \sim 340\text{nm} \)) are deposited by e-beam evaporator for double-layer Schottky gate contact. Finally, the lift-off process is performed with 1 to 1 mixture of methanol and dichloromethane (CH\(_2\)Cl\(_2\)).
Figure 2.6 E-beam dose test results showing actual gate length vs dosage using 25 nm long gate in the layout. E-beam current and field are 100 pA and 100 kV, respectively. Tri-layer e-beam resist stack is used: 950 k-PMMA/Co-polymer/50k-PMMA.
Chapter 3: Qualitative Characterization of Trapping effects in AlGaN/GaN HEMTs

In this chapter, characterization of trapping effects are described to understand trapping effects in AlGaN/GaN HEMTs using short drain current transient and static/dynamic current-voltage ($I-V$) measurements. HEMTs under tests show different current dispersions depending on post-gate annealing (PGA) conditions, which are good specimens for trap characterization. PGA under the optimum condition improves RF and power performance as well as breakdown performance as described in Chapter 1. In the following sections, PGA effects on HEMT performance are interpreted in terms of trap activity based on pulsed $I-V$ measurements. The trap characterization methods and its interpretation can be applicable for examining other processing-induced effects on trap activity in AlGaN/GaN HEMTs.

3.1 Introduction of pulsed current–voltage ($I-V$) characterization

In general, pulsed $I-V$ measurement techniques have been developed for analysis of $I-V$ characteristics of active devices for radio frequency (RF) /microwave device operation while static $I-V$ measurements generally include self-heating and trapping effects varying with applied biases, causing inaccuracy analysis for RF/microwave operation [107]. For pulsed $I-V$ measurements, voltage signals of square pulse are
applied from a static quiescent bias (QB) point to obtain currents at the end of the pulse duration and, then, devices under test come back to and stay at the QB point until the next voltage pulse is applied. If the pulse duration is short enough compared with separation time between consecutive voltage pulses, both temperature and trapping effects are dependent mainly on QB point. In case of a very short pulse duration, thermal effects are considered to be invariant and trapping effects are frozen when emission/capture time constants is smaller than the pulse duration. Thus, by appropriately choosing QB points and pulse duration/separation time, trapping effects can be analyzed in a quasi-static mode with minimal thermal effect.

Pulsed I-V measurement technique as described above is very useful for analysis of trapping effects in AlGaN/GaN HEMTs for high-power and high-speed applications. However, for more accurate trap characterization, careful attention should be paid to interpretation of pulsed I-V characterization results since 1) DC $I-V$ characteristics can not be a reference for quantitative analysis (See Chapter. 5), 2) some bias points (i.e., Class A type) can create heating or hot-electron effects at AlGaN/GaN interface and 3) some actual biases forced onto active traps are different depending on device geometry even if the external bias conditions are the same for HEMTs to be analyzed. The pulse bias conditions are illustrated in Section 3.2.2 to minimize any heating effects. In this chapter, DC $I-V$ s are used as a reference for comparison and single-geometry HEMTs
are analyzed. Based on pulsed $I-V$ and transient drain current measurements, time-
dependence of trap activity and trapping effects on pulsed $I-V$ characteristics in term of
capture/emission time constants are discussed.

3.2. Experimental details for PGA study and DC/pulsed $I-V$ characterization of
AlGaN/GaN HEMTs

This section describes preparation of AlGaN/GaN HEMTs for PGA study, and
coloration of trap activity in AlGaN/GaN HEMTs with/without post-gate annealing
and interpretation of impact of PGA on device performance based on DC and pulsed $I-V$
measurements.

3.2.1 Preparation of testing HEMTs

AlGaN/GaN HEMTs on SiC substrates to be analyzed in this chapter were
fabricated by standard HEMT process as described in Chapter 2. AlGaN/GaN HEMTs
with a gate-length of 0.2 µm, a gate width of 100 µm and a source to drain spacing of 3
µm are used to investigate PGA effects. The wafer was cleaved to three samples. Sample
1 was not annealed for reference. Samples 2 and 3 were annealed at 400 °C for 10 and 20
minutes, respectively, in a furnace with N$_2$ ambient. After annealing, the breakdown
voltage of the annealed samples 2 and 3 increased dramatically from ~ 35 V to higher than 180 V. The maximum drain current of sample 2 in the DC $I$–$V$s had improvement but the sample 3 had slightly degradation in comparison with the reference sample [54]. The breakdown performance will be discussed in Section 3.3.

### 3.2.2 Bias conditions for Pulsed $I$–$V$ characteristics

The pulsed I-Vs are characterized at different QB conditions; $(V_{DSQ}, V_{GSQ}) = (0 \text{ V}, 0 \text{ V}), (0 \text{ V}, -5 \text{ V}),$ and $(7 \text{ V}, -5 \text{ V})$ as shown in Figure 3.1. Under these three QBs, there is essentially no drain current flowing in the channel. Electrons are depleted at QBs of $(V_{DSQ}, V_{GSQ}) = (0 \text{ V}, -5 \text{ V})$ and $(7 \text{ V}, -5 \text{ V})$ and some of them are trapped, while there is no electron trapping at $(V_{DSQ}, V_{GSQ}) = (0 \text{ V}, 0 \text{ V})$. The pulse widths (PWs) of 200 ns, 500 ns, 10 μs, and 100 μs are used with a pulse separation of 1 ms. The DC and pulsed $I$–$V$ curves measured at $V_{GS} = 0 \text{ V}$ are used to investigate the trapping behavior of three samples without annealing and with 10-min and 20-min annealing at 400 °C.
Figure 3.1 Bias conditions in pulse $I-V$ measurements (drawings are not in scale). Pulse widths are 0.2, 0.5, 10, and 100 $\mu$s and pulse separation is 1 ms.
3.2.3 Current dispersion between DC and pulsed $I–V$ characterization

This subsection illustrates interpretation of trapping effects in pulsed $I–V$ characteristics of AlGaN/GaN HEMTs by comparing DC $I–V$ results. First, when pinch-off biases of $(V_{DSQ}, V_{GSQ}) = (7 \text{ V}, -5 \text{ V})$ is used as a QB point, DC and pulsed $I–V$ curves measured at $V_{GS} = 0 \text{ V}$ are compared as in Figure 3.2. As the pulse width increases, current dispersions between DC and pulsed $I–V$ decreases for all three samples. Generally, under this quiescent bias, the device is at off-state. Some electrons are captured by traps at Ni/AlGaN interface and on the ungated AlGaN surface near the gate edge. The current dispersion due to this electron trapping between DC (solid) and pulse $I–V$s of each sample can be interpreted with the density and emission time constant ($t_E$) of traps involved in electron capturing. For example, the dispersion between DC and 0.2 $\mu$s $I–V$s is directly related to the density of active traps with emission time constants ($t_E$) of longer than 0.2 $\mu$s. This is because that if the pulse width is shorter than $t_E$, electrons captured by traps do not have enough time to be fully emitted. But if the pulse width is long enough, some of the trapped electrons can be detrapped and contribute to drain current. That is why pulsed $I–V$s with a longer pulse width show a larger drain current and a smaller current dispersion.
As shown in Figure 3.2, the drain current ($I_D$) dispersion between DC and the 0.2 $\mu$s pulsed $I-V$s in the non-annealed HEMTs is much larger than that in the 10-minute
annealed devices, indicating a larger number of traps are removed during the post-gate annealing. The $I_D$ difference between DC and 10/100 $\mu$s pulse $I$–$V$ curves in the non-annealed devices is negligible but some $I_D$ dispersion in the 10-min annealed sample is still observed, which suggests that a small number of traps with a long time constant are created during the post-gate annealing, though the total number of traps is significantly smaller than that of non-annealed devices. Severe current dispersion in 20-minute annealed HEMTs with any pulse widths indicates that further annealing creates a much larger density of traps with a long time constant. This indicates that the PGA process removes traps with a shorter $t_E$ and induces or activates traps with a longer $t_E$.

On the other hand, when a quiescent bias point of $(V_{DSQ}, V_{GSQ}) = (0 \text{ V}, 0 \text{ V})$ is applied, drain current level in pulsed $I$–$V$ characteristics is much higher than that in DC $I$–$V$ s. Figure 3.3 shows DC and pulsed $I$–$V$ characteristics at $V_{GS} = 0 \text{ V}$ with different pulse widths. As the pulse width increases, decrease in the saturation drain current is observed in the pulsed $I$–$V$s of three samples. In this case, since the QB condition is the same as equilibrium, again, it is considered that there is no initial electron trapping under the QB point. Furthermore, 0.2 $\mu$s pulse width is too short for electrons to be captured. A long pulse width allows some electrons to have sufficiently long time for some electrons to be trapped and is possibly long enough for some heat to be accumulated. So a longer pulse width results in a smaller drain current.
Figure 3.3 DC $I$–$V$ (solid) and pulsed $I$–$V$ at $V_{GS} = 0\text{V}$ and a quiescent bias point of $(V_{DSQ}, V_{GSQ}) = (0\text{ V}, 0\text{ V})$ at pulse widths of 0.2 $\mu\text{s}$ (dash), 0.5 $\mu\text{s}$ (dot), 10 $\mu\text{s}$ (dash dot), and 100 $\mu\text{s}$ (dash dot dot). [pulse separation: 1ms]: (a) unannealed HEMTs, HEMTs annealed at 400°C for 10 minutes (b) & 20 minutes (c), and (d) bias conditions
Note that there has been limited information about thermal time constant in AlGaN/GaN HEMTs. Recently, Kuball et al. reported thermal time constant of \( \sim 10 \mu s \) for 150 \( \mu m \)-wide and 5 \( \mu m \)-long ungated AlGaN/GaN devices on SiC using micro-Raman spectroscopy with combination of laser pulse and electrical pulse, and showed that the device temperature changes rapidly within the first 1 \( \mu s \) of electrical pulse for 0.25\( \mu m \)-long gate AlGaN/GaN HEMTs on SiC [108]. However, it is unclear 1) whether their analysis conditions can neglect trapping effects within 2 \( \mu s \) electrical pulse they used, and 2) whether their extracted thermal time constant using 50 \% duty cycle of the electrical pulse for their analysis is the same as that with less than 0.1\% duty cycle. Dispersion of the saturation current between the 0.2 \( \mu s \) pulsed \( I-V \) and DC \( I-V \) of non-annealed and 10-min annealed HEMTs is smaller than that of 20-min annealed HEMTs. This suggests that the devices annealed at 400 \( ^\circ C \) for 20 minutes have a much larger density of traps with a capture time constant \( (t_C) \) of longer than 0.2 \( \mu s \). The dispersion between 10 \( \sim \) 100 \( \mu s \) pulsed \( I-V \) s and DC \( I-V \) s are observed in both annealed HEMTs. Again, this indicates that the post-gate annealing remove traps with a short capturing time constant and creates traps with a long capturing time constant.

Figure 3.4 shows 10 \( \mu s \) pulsed \( I-V \) s of non-annealed and annealed AlGaN/GaN HEMTs at three different QBs. The 10 \( \mu s \) pulsed \( I-V \) s of the 10-minute annealed devices
still show current dispersion at any QB conditions while the non-annealed one does not show any current dispersion (Figure 3.4(a)). This indicates that since non-annealed HEMT doesn’t have any traps with longer than capture and emission time constants of 10 μs, PGA creates or activates traps with time constants of longer than 10 μs. The pulse $I-V$s of the 10-minute annealed devices at $(V_{DSQ}, V_{GSQ}) = (7 \text{ V}, -5 \text{ V})$ show larger current dispersion if the drain voltage is lower than 7 V than at $(V_{DSQ}, V_{GSQ}) = (0 \text{ V}, -5 \text{ V})$. However, 20-minute annealed devices still show current dispersion even if the drain voltage is higher than 7 V, indicating that further annealing creates or activates deeper trap centers. The difference in current dispersion between $(V_{DSQ}, V_{GSQ}) = (0 \text{ V}, -5 \text{ V})$ and $(V_{DSQ}, V_{GSQ}) = (7 \text{ V}, -5 \text{ V})$ is because $V_{DSQ} = 7 \text{ V}$ causes extension of the trapped region toward drain contact and more electron trapping due to higher reverse field near the drain-side gate edge than $V_{DSQ} = 0 \text{ V}$. This will be discussed more in Chapter 5.
Figure 3.4 DC and 10 μs pulsed $I-V$s of the annealed AlGaN/GaN HEMTs at different quiescent bias points at a fixed pulse separation of 1 ms: (a) non-annealed, (b) annealed at 400 °C for 10 minutes, and (c) annealed at 400 °C for 20 minutes.
3.2.4 Correlation of current dispersion with pulse width and time constants of active traps

Figure 3.5 shows drain current dispersions of the non-annealed and annealed AlGaN/GaN HEMTs at different QBs and pulse widths to evaluate PGA effects. Current dispersion between the drain current ($I_{DC}$) in DC $I$–$V$ and the drain current ($I_D$) in the pulsed $I$–$V$ s is defined as $I_D$–$I_{DC}$ measured at $(V_{DS}, V_{GS}) = (7 \, \text{V}, \, 0 \, \text{V})$. If devices are pinched-off at quiescence, some electrons are captured by traps. At such QB biases, the drain current dispersion is caused by incomplete emission of the captured electrons if the applied pulse width is shorter than $t_E$ of traps. At a QB of $(V_{DSQ}, V_{GSQ}) = (0 \, \text{V}, \, 0 \, \text{V})$, the dispersion of current increase is attributed to less electron capturing if the applied pulse width is shorter than the capture time constant ($t_C$). As the pulse width increases, the current dispersion in the non-annealed and annealed devices decreases at any QBs. When QBs of $(V_{DSQ}, V_{GSQ}) = (0 \, \text{V}, \, -5 \, \text{V})$ and $(7 \, \text{V}, \, -5 \, \text{V})$ are used, the dispersion in the non-annealed devices is almost identical. However, the annealed devices show slightly larger current dispersion at $(V_{DS0}, V_{GS0}) = (7 \, \text{V}, \, -5 \, \text{V})$ than at $(V_{DS0}, V_{GS0}) = (0 \, \text{V}, \, -5 \, \text{V})$. Again, this indicates that some electrons are trapped in the extended region between gate and drain if a positive voltage is biased at drain after PGA.

In addition, the current dispersion of AlGaN/GaN HEMTs measured at QBs of off-state biases shows different dependences on pulse width before and after PGA. In the non-
annealed devices, current dispersion is ~31 mA in the 0.2 μs pulsed I-Vs. For the 10-minute annealed devices, the current dispersion is ~10 mA at the same pulse width, indicating a larger number of traps are removed during PGA.

Figure 3.5 Dispersion between drain currents of static and dynamic I–V's of AlGaN/GaN HEMTs as a function of pulse widths at different QBs: (a) non-annealed HEMTs. (b) annealed HEMTs at 400 °C for 10 minutes and (c) annealed HEMTs at 400 °C for 20 minutes.
However, for the 10-minute annealed devices, there is still current dispersion even if the pulse width is larger than 10 μs. Again, this suggests that there are a small number of traps with a long time constant created during PGA, though the total number of traps is significantly smaller than that of non-annealed devices. 20-minute annealed devices, under the pinch-off QBs, exhibited a similar trend to 10-minute annealed devices. However, further annealing at 400 °C increases the current dispersion, indicating that the number of traps with $t_E > 10$ μs created during PGA increases as the annealing time increases.

### 3.2.5 Transient drain current characteristics

Figure 3.6 shows short drain current transient normalized by DC drain current ($I_{DC}$) at $(V_{DS}, V_{GS}) = (7 \text{ V}, 0 \text{ V})$. The bias was pulsed up from at $(V_{DS}, V_{GS}) = (7 \text{ V}, -5 \text{ V})$ to $(7 \text{ V}, 0 \text{ V})$. The non-annealed devices show the clear fast transient within a few μs after pulsing-up. Based on these transient measurements, emission time constants are extracted using the following exponential decay functions:

$$I_D(t) = I_{DC}(1 - I_0 \exp[-t/\tau]).$$  \hspace{1cm} (3-1)

$$I_D(t) = I_{DC}(1 - I_1 \exp[-t/\tau_1] - I_2 \exp[-t/\tau_2]).$$  \hspace{1cm} (3-2)
where $I_{DC}$ is the DC drain current at $(V_{DS}, V_{GS}) = (7 \text{ V}, 0 \text{ V})$, $\tau$ is emission time constant, and $I_0$ and $I_2$ are fitting constants.

Figure 3.6 (a) Normalized transient characteristics of the unannealed HEMTs (solid line), and HEMTs annealed at 400$^\circ$C for 10 minutes (dashed line) & 20 minutes (dash-dot-dot line) and (b) transients in the first 10 $\mu$s. The biases are pulsed up from $(V_{DS}, V_{GS}) = (7 \text{ V}, -5 \text{ V})$ to $(V_{DS}, V_{GS}) = (7 \text{ V}, 0 \text{ V})$. 

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The transient spectra of non-annealed devices and 10-minute annealed devices fit well to Eq. (3–1). The transient behavior of devices annealed for 20 minutes show better fitting to Eq. (3–2) with double exponential decay functions. The extracted time constants of the non-annealed and 10-minute annealed devices are ~ 0.5 μs and ~ 9.2 μs, respectively. The 20-minute annealed devices have emission time constants of ~ 21.6 μs and ~ 1.25 ms. These extracted time constants show clearly that the post-annealing process removes traps with a short \( t_E \) and induces traps with longer \( t_E \). These extracted emission time constants explain pulse width-dependent current dispersion trends of non-annealed and annealed HEMTs as shown in Figure 3.5.

3.3 Relationship between gate-leakage current/breakdown performance and trap energy level

In this section, modification of trap activity in AlGaN/GaN HEMTs without and with PGA will be described in terms of time constants and activation energy. Time constants and activation energies of traps were extracted from drain current transients at different temperatures and from temperature-dependence of emission time constants. Particularly, change in the activation energy of traps participating in trapping/detrapping effect will be connected to breakdown voltage improvement. To examine gate
leakage/breakdown mechanism before and after post-gate annealing, two samples were chosen: one was without annealing and another was annealed at 400 °C for 20 minutes in a furnace with N₂ ambient. In order to understand the role of these traps in gate leakage/device breakdown, reverse gate current measurements and temperature-dependent drain current transient measurements of the non-annealed and 20-minute annealed HEMTs were performed. The bias was pulsed up from at \((V_{DS}, V_{GS}) = (7 \, \text{V}, -5 \, \text{V})\) to \((7 \, \text{V}, 0 \, \text{V})\). The measurement temperature range was from 295 K to 368 K and activation energies of the traps were extracted from temperature dependent curve of an emission time constant.

To avoid the physical breakdown of the 20-minute annealed devices, current compliance in gate leakage measurements was set at 20 nA, corresponding to gate current \((I_G)\) of 0.2 μA/mm. As shown in Figure 3.7, at \(I_G = 0.2 \, \mu\text{A/mm}\), the gate-to-drain voltage \((V_{DG})\) is about −110 V for annealed HEMTs while \(V_{DG}\) of the non-annealed devices is ~ −40 mV, indicating significant improvement in gate leakage by the PGA process. At \(V_{DG} = −35 \, \text{V}\), the gate leakage current is ~ 1 mA/mm for non-annealed devices.
3.4 Temperature-dependent transient drain current characterization

As described above, non-annealed HEMTs have active traps with a very short $t_E$ but 20-min annealed HEMTs show very slow drain current transient due to traps with longer $t_E$s. It is expected that energy levels of active traps corresponding to these time
constant will be different. To identify trap energy levels, the emission time constants of active traps are extracted from the drain current transient characteristics measured at different temperatures, using Eq. (3–1) and (3–2) as described Section. 3.2.3. The bias is pulsed up from $(V_{DS}, V_{GS}) = (7 \ V, -5 \ V)$ to $(7 \ V, 0 \ V)$. At 295 K, one time constant of $\sim 0.5 \ \mu s$ is extracted for the non-annealed HEMTs and two different time constants ($\tau_1$ of $\sim 21.6 \ \mu s$ and $\tau_2$ of $\sim 1.25 \ ms$) are extracted for the 20-minute annealed HEMTs. For the extraction of the activation energy in 20-minute annealed HEMTs, $\tau_1$ only is used since $\tau_2$ is outside the range of total measurement time. The temperature-dependence of $t_E$ is described by using the classical Arrhenius equation:

$$
\tau^{-1} = C T^2 \exp(-E_A/kT),
$$

(2–3)

where $T$ is the temperature in Kelvin, $E_A$ is the activation energy, $\tau$ is the time constant, $k$ is the Boltzmann constant, and $C$ is a fitting factor. Figure 3.8 shows the temperature-dependence of emission time constant in the non-annealed and 20-minute annealed HEMTs. The activation energy is extracted from the slope in Figure 3.8. The activation energies of those traps are determined to be $\sim 38 \ meV$ in the non-annealed HEMTs and $\sim 0.31 \ eV$ in 20-minute annealed ones at $(V_{DS}, V_{GS}) = (7 \ V, 0 \ V)$. The temperature range for the annealed devices [Figure 3.8(b)] is from 343 K to 368 K. In the lower temperature range, $t_E$ does not follow the classical Arrhenius equation. Namely, the thermally
activated electrons captured by traps are not noticeable in drain transient current. Because of the high activation energy, lattice scattering due to heating effect can prevail over the thermal activation of the trapped electrons.

![Graph showing temperature dependence of the time constant extracted from the drain current transient curves.](image)

Figure 3.8 Temperature dependence of the time constant extracted from the drain current transient curves. The temperature ranges from 295 K to 363K for non-annealed HEMTs [(a)] and from 333 K to 363K for 20-minute annealed HEMTs [(b)]. The gate is pulsed from $V_{GSQ} = -5$ to $V_{GS} = 0$ V and the drain voltage is 7 V.

Physically, it is considered that reaction between Ni Schottky gate metal and AlGaN during the PGA can remove the shallow traps and/or induce the deeper traps at
Ni/AlGaN interface. Changes in electrical properties at Ni/AlGaN interface and chemical composition over the ungated AlGaN surface near the gate edge will be discussed in Chapter 4. We suggest that the shallow level traps in the non-annealed HEMTs are the most probable source for the current dispersion in DC and pulsed $I−V_s$, and a low breakdown voltage. The significant breakdown voltage improvement is attributed to the removal of traps with a short $t_E$ of 0.5 μs at 295 K and an activation energy of 38 meV at $V_{DS} = 7$ V. The shallow level traps may be due to oxygen impurities substituting for nitrogen vacancies. However, oxygen donor levels in AlGaN are deeper than the extracted shallow trap energy level of ~38 meV while ~38 meV is similar to those in GaN. For example, McCluskey et al. reported that oxygen impurities in AlGaN with higher Al concentration act as deep level traps with the activation energies of 0.12 eV, 0.19 eV, and 0.24 eV for 39 %, 44 %, and 0.49 % Al fraction [109]. Stampfl et al. also theoretically showed that transition of the shallow donor into a deep level can occur at high Al fraction [110]. Seghier et al. [111] reported continuous shallow donor levels of 50 meV to 110 meV for 10 % and 30 % Al concentration in AlGaN/GaN heterostructures while there was no clear evidence that the shallow donors are due to oxygen impurities. At this moment, the physical origin of 38 meV trap level is not clear but deep level (0.31 eV) traps can be attributed to oxygen impurities.
Figure 3.9 shows an energy band diagram to explain gate leakage/breakdown mechanism of the non-annealed and annealed AlGaN/GaN HEMTs under a QB of off-state [i.e., $(V_{DS}, V_{GS}) = (7 \text{ V}, -5 \text{ V})$]. The QB leads to device pinch-off and some electrons are captured at trap centers. Symbol A and B in Figure 3.9 are designated as electron trapping in shallow levels (non-annealed HEMTs) and deeper levels (annealed ones), respectively. The capturing process is affected by applied electric field between the gate and the channel. On the contrary, the emission process of the trapped electrons consists of thermionic emission (TE) and field-assisted tunneling [18, 23] such as thermionic-field emission (TFE) and field emission (FE). At a certain electric field and temperature, the emission current by electrons emitted from shallow trap centers is much higher than the electron emission from the deeper levels. This is because electrons captured by shallow traps can be thermally activated more easily than those by deep traps. Thus, the annealed devices exhibited much lower gate leakage current and higher breakdown voltage than the non-annealed ones.
Figure 3.9 Schematic energy band diagram for the Ni/AlGaN/GaN HEMTs near the drain-side gate edge to describe the gate leakage/breakdown mechanism under two bias conditions of (a) \((V_{DSQ}, V_{GSQ}) = (7 \, \text{V}, -5 \, \text{V})\) and (b) \((V_{DSQ}, V_{GSQ}) = (7 \, \text{V}, 0 \, \text{V})\).

In addition, the deep traps are responsible for slow drain current transient. Since \(t_E\) for 20-min annealed HEMTs does not follow the classical Arrhenius equation in the lower temperature range from 295 K to 343 K as described above, emission of the

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trapped electrons at \((V_{DS}, V_{GS}) = (7 \text{ V}, 0 \text{ V})\) [Figure 2.9(b)] for the annealed HEMTs is considered to be mainly due to field emission. Then, if the vertical field is not strong enough, thermal activation process should be involved in the emission process but will be long because of the high energy barrier. As a result, drain current is slowly recovered in drain current transient characteristics when the bias pulsed up \((V_{DS}, V_{GS}) = (7 \text{ V}, -5 \text{ V})\) to \((V_{DS}, V_{GS}) = (7 \text{ V}, 0 \text{ V})\). On the other hand, emission of trapped electrons at shallow traps in non-annealed HEMTs can be caused by both thermionic and field-assisted emissions, leading to a faster drain current recovery.

Thus, our results show that the dominant emission mechanisms are different before and after PGA. The captured electrons at deep traps in annealed devices are emitted mainly due to field-assisted tunneling.

3.5 Summary

Trapping effects in AlGaN/GaN HEMTs with and without PGA have been investigated based on DC and pulsed \(I-V\) characterizations, temperature-dependent drain current transient measurements, and reverse-gate current characterizations. Current dispersion between DC and pulsed \(I-V\) was interpreted in terms of time constants and energy level of trap. It is demonstrated that PGA modifies trap activity in AlGaN/GaN HEMTs. The PGA process removes shallow traps with an activation energy of \(\sim 38 \text{ meV}\)
and $t_E$ of $\sim 0.5 \, \mu s$ at 295 K and induces deeper traps at least with an activation energy of $\sim 0.31 \, eV$ and $t_E$ of $\sim 21.6 \, \mu s$ at 295 K. Shallow traps result in fast drain current transient and high reverse gate leakage current while deep traps lead to slow current recovery but a small leakage current. We suggest that our methodology for trap characterization can be utilized for process monitoring and optimization to minimize trapping effects.
Chapter 4: Investigation of Ni/AlGaN Interface and Ungated Free AlGaN Surface

Before and After PGA

4.1 Introduction

This chapter covers modification of electrical properties at Ni/AlGaN interface and compositional change of the free AlGaN surface before and after annealing. Change of electrically active states at Ni/AlGaN interface and the free AlGaN surface will be correlated with trap activity in AlGaN/GaN HEMTs with/without post-gate annealing (PGA).

As discussed in Chapter 1 and 3, PGA process under an optimum condition can improve RF/Power performance since PGA reduces density of active traps with shallow energy level, leading to less current dispersion and increased breakdown voltage. However, it has been unclear how PGA changes electrical properties of the existing active traps in AlGaN/GaN HEMTs. The following description provides a short review about annealing effects on Schottky contacts in AlGaN/GaN heterostructures and objectives of EBIC and XPS analyses.

Annealing effects on Schottky contacts in AlGaN/GaN heterostructures have been frequently reported by showing improvement in electrical properties such as reduction of reverse leakage current, or/and improvement of Schottky barrier height or/and breakdown
Miura et al. proposed that annealing process could reduce interface traps between metal and AlGaN or form the island-like Ni oxide, leading to reduction in leakage current [49, 50]. Increase of the barrier height can be due to change in effective dielectric constant of the material or intimate contact formation between metal and AlGaN [112]. In addition, it has been reported that annealing in oxygen could create Ga vacancies [51], forming Schottky metal oxides such as p-NiO [52] or IrO$_2$ which has a high work function [51], leading to increased barrier height. Many works of annealing effects on AlGaN/GaN Schottky diodes have been reported so far in terms of surface/interface states using electrical characterization. However, the exact mechanism of the post-annealing effects is not completely understood in AlGaN/GaN Schottky diodes.

Two physical changes by PGA are expected: the modification of Schottky metal/AlGaN interface states and unintentional reaction (i.e., oxidation) on the free AlGaN surface. Both cases affect trapping activities of surface/interface states, e.g., trap-assisted tunneling [16, 18] as a leakage current mechanism, and surface trapping as virtual gate formation causing current dispersion [14]. The following sections cover investigation of physical origin of PGA effect in AlGaN/GaN heterostructures by examining Schottky metal/AlGaN interface using 1) electron beam induced current
EBIC analysis and electrical measurements, and 2) X-ray photoelectron spectroscopy (XPS) analysis.

4.2 Electron beam induced current (EBIC) analysis at Ni/AlGaN interface

EBIC analyses of Ni/AlGaN/GaN diodes are compared with electrical characteristics such as reverse leakage current, and Schottky barrier height ($\phi_B$) to examine the Ni/AlGaN interface properties. Then, the effect of thermal reaction at the Schottky metal/AlGaN interface during PGA on interface states and AlGaN/GaN Schottky diode performance will be discussed. Finally, based on EBIC results showing modification of electrically active states at the Schottky metal/AlGaN interface, post-gate annealing effects on pulsed $I$–$V$ measurements of AlGaN/GaN HEMTs [16, 113] will be qualitatively interpreted.

4.2.1 Experimental procedures for EBIC analysis

Ni/Au AlGaN/GaN Schottky diodes on a sapphire substrate with different areas ($7.07 \times 10^{-4}$, $1.2 \times 10^{-3}$, and $1.1 \times 10^{-3}$ cm$^2$) were fabricated by the standard process as described in Chapter 2. To investigate annealing effects on AlGaN/GaN diodes, the as-
deposited diodes were first examined using current-voltage (I-V) measurements and EBIC analysis. Then, the same diodes were annealed at 400 °C for 20 minutes in nitrogen ambient and characterized with the same techniques. Again, after two further annealings for 50 and 170 minutes at the same temperature, the same analyses were performed. Before annealing and after each annealing step, Schottky diode performance such as reverse leakage current, and $\phi_B$ and $n$ was compared. $\phi_B$ and $n$ were extracted by fitting forward biased I-V curves of the Schottky diode to the thermionic emission current equation. Change in electrically active states at the Schottky metal/AlGaN interfaces was examined by EBIC image characterization at an electron-beam energy of 30 keV at zero volt bias. Since the incident electron beams induce minor damage to Schottky diodes, which may lead to slight increase in reverse leakage current, the annealing followed by each EBIC analysis was performed for enough time to recover the damage and achieve further reduction of the leakage current by about one order of magnitude. Surface morphology in AlGaN/GaN heterostructures was probed using atomic force microscopy (AFM) to compare with EBIC images. Figure 4.1 shows a schematic energy band diagram of Ni/AlGaN/GaN Schottky diodes showing a basic principle for EBIC analysis. The incident electron beam with energy higher than the bandgap energy creates electron-hole pairs, which are separated by the existing electric field across AlGaN barrier. Some of the generated holes can be recombined with the existing negatively-charged interface
states at Ni/AlGaN interface. The recombined e-beam-generated holes don’t contribute to electron-beam-induced current, resulting in a dark spot on EBIC images.

Figure 4.1 Schematic diagram for a basic principle of EBIC analysis in AlGaN/GaN HEMTs showing that e-beam-generated electron-hole pairs are separated by the electric field across AlGaN barrier, the generated hole can be recombined with negatively charged interface states at Ni/AlGaN surface and don’t contribute to electron-induced beam current.
4.2.2 Comparison between AFM of base surface AlGaN/GaN heterostructures and EBIC images of Ni/AlGaN/GaN Schottky contacts

Figure 4.2 shows AFM image of the free surface in the AlGaN/GaN heterostructures and EBIC image of the as-deposited diode with Schottky contact area of \(1.2 \times 10^{-3}\) cm\(^2\). The AFM image (2 \(\mu\)m \(\times\) 2 \(\mu\)m) of the surface shows wavy surface with RMS roughness of \(\sim 0.276\) nm and black pits with a density of \(\sim 6 \times 10^8\) /cm\(^2\), corresponding to the dislocation density of the material. This is comparable with the reported results of n-GaN on sapphire [114]. The observed dislocations are expected to act as sites interacting with charged carriers and leakage current paths. As can be seen in the EBIC image of the as-deposited Schottky diode (Figure 4.2(b)), many black spots are widely distributed. The black spots in EBIC images are attributed to recombination between electrically active states at Ni/AlGaN interface and e-beam generated holes. The density of the black spots is roughly \(2\sim 5 \times 10^{-8}\) cm\(^2\) by a rough manual count. Based on Monte Carlo simulation results (CASINO), most of the electrons were expected to pass within a beam diameter of \(< \sim 200\) nm when they reached the AlGaN surface in our EBIC analyses. Thus, some irregular shapes of the dark areas instead of dot shape may be due to overlap between low EBIC signals of adjacent recombination sites. Nevertheless, the EBIC image does suggest that these black spots, which are corresponding to the
recombination sites, are related mostly to dislocations and other interface states [17]. Therefore, the negatively charged states are considered to be acceptor-like states below the Fermi level at Ni/AlGaN interface.

Figure 4.2 AFM image (2 μm × 2 μm) showing the surface morphology in AlGaN/GaN heterostructure (a) and EBIC images of the as-deposited AlGaN/GaN Schottky diodes (b).
4.2.3 Electrical characterization and EBIC images of Ni/AlGaN/GaN Schottky diodes

Figure 4.3 shows \( I-V \) characteristics of the diode with Schottky contact area of 1.2\( \times 10^{-3} \) cm\(^2\) after 20-min, 50-min, and 170-min annealing at 400 °C. Reverse leakage current densities (\( J_{\text{reverse}} \)) were \(-6.89 \times 10^{-2}, -1.29 \times 10^{-2}, -2.25 \times 10^{-3}, \) and \(-1.34 \times 10^{-3} \) A/cm\(^2\), respectively, at an applied bias of \(-5\) V.

![Figure 4.3 I–V characteristics of the diode with Schottky contact area of 1.2\( \times 10^{-3} \) cm\(^2\) before annealing (solid) and after 20-min (dash), 50-min (dot), and 170-min (dash-dot) annealing at 400 °C.](image)
To extract saturation current density ($J_S$), $n$ and $\phi_B$ from these forward-biased $I-V$ curves, the thermionic emission $I-V$ relationship was used in the range where the series resistance ($R_S$) is negligible. Richardson constant ($A^*$) is 33.744 $\text{A/cm}^2\text{K}^2$ from $4\pi qk^2m^*/h^3$ where $k$ is Boltzmann’s constant, $h$ is Plank’s constant, and $m^*$ in Al$_{0.29}$Ga$_{0.71}$N was linearly interpolated from $m^* = 0.20m_e$ in GaN and $m^* = 0.48m_e$ in AlN where $m_e$ is the free electron rest mass [86]. $\phi_B$ increased and $J_S$ decreased as the Schottky diodes were annealed. On the other hand, $n$ decreased after annealing but increased after 170-min annealing. In this study, the number of Schottky diodes examined is limited to three since large area contacts are required for EBIC analysis. $\phi_B$ and $J_S$ shown in Figure 4.4 (a) are average values of tested devices.

In addition, average reverse leakage current densities ($J_{\text{reverse}}$) of three diodes were −6.46×$10^{-2}$, −1.13×$10^{-2}$, −2.76×$10^{-3}$, and −1.49×$10^{-3}$ $\text{A/cm}^2$ before annealing, and after 20-min, 50-min, and 170-min annealing at 400 °C, respectively, at an applied bias of −5 V. The series resistance ($R_S$) was extracted from the slope in the plot of $dV/d(\ln J)$ with respect to $J$ where $J$ is current density [115]. All three diodes showed a similar trend that $R_S$ decreased slightly after 20-min annealing and increased after 50-min. Figure 4.4(b) shows the values of series resistance of a typical diode annealed at different conditions. Since the devices have different dimensions, their series resistance values are not averaged. The initial decrease of $R_S$ after 20-min annealing can be explained by removal
of a native oxide layer due to thermal reaction at metal/AlGaN interface [115]. Increase of $R_s$ after further annealing may be due to formation of highly resistive layer at metal/AlGaN interface [115] or unintentional oxidation of metal.

Figure 4.4 Schottky diode device parameters extracted from these forward-biased I-V curves as a function of annealing time: (a) Barrier height and Saturation current, (b) ideality factor and series resistance.
Figure 4.5 shows EBIC images of the same diode with Schottky contact area of 1.2×10⁻³ cm² after 20-min, 50-min, and 170-min annealing at 400 °C and scanning electron microscopy (SEM) image after 170-min annealing at 400 °C. Compared with the EBIC image of the as-deposited diode (Figure 4.2(b)), area of dark spots decreased after 20-min (Figure 4.5(a)) and 50-min annealing (Figure 4.5(b)) while change in surface morphology after 50-min annealing was not noticeable from their SEM images as in Figure 4.6. This indicates that the post-annealing decreased the density of Schottky metal/AlGaN interface states, acting as recombination sites to reduce EBIC. Based on trap-assisted tunneling model as a reverse leakage current mechanism, it is considered that the reduction of recombination sites led to decrease in the reverse leakage current densities. Note that black/white contrast of EBIC images after annealing is not good enough for quantitative analyses of dark area compared with that before annealing. The EBIC image of 170-min annealed Schottky contact (Figure 4.5(c)) had additional dark spots (Region A) which are not shown in its SEM image (Figure 4.5(d)). The SEM image (Figure 4.5(d)) showed rough surface morphology and several dark spots. The black spots shown in the same position of both EBIC and SEM image may be due to non-electrically active sites but highly resistive phase such as NiOx. It seems that area of the extra spots after 170-annealing was decreased. However, we should note that the change of metal surface morphology after 170-annealing can affect EBIC images.
Figure 4.5 EBIC images of the diode with Schottky contact area of $1.2 \times 10^{-3}$ cm$^2$ after 20-min (a), 50-min (b), and 170-min annealing (c) at 400 °C. (d) is SEM image of 170-min annealed Schottky diode corresponding to EBIC image (c). Black spots in Region A are shown in EBIC image (c) but not shown in SEM image (d).
Figure 4.6 EBIC and SEM images of an AlGaN/GaN Schottky diode before and after 50-min annealing at 400 °C.
From the results of Figure 4.5, we suggest that thermal reaction at metal/AlGaN interface during post-annealing electrically passivated the active interface states including some of dislocations. The post-annealing-induced passivation of the Ni/AlGaN interface states like dislocations or/and possibly nitrogen vacancies might be correlated with the unintentional oxidation of Ni [50] and surface cleaning of contamination AlGaN surface [56, 112]. In addition, the results support early reports by Kim et al. and Karmalkar et al. that interface states assist electron tunneling leading to the reverse leakage current [16, 18].

The black spots in EBIC images are attributed to recombination between electrically active states at Ni/AlGaN interface and e-beam generated holes. The density of negatively charged states, which are considered to be acceptor-like states below the Fermi level at Ni/AlGaN interface, decreased after the post-annealing, indicating that the post-annealing passivated the active interface states to neutralized ones. Figure 4.7 shows energy band diagrams at equilibrium of as-deposited and annealed Ni/AlGaN/GaN Schottky diodes based on EBIC and $I-V$ results. It was observed that, after post-annealing, the barrier height of the Schottky diodes increased while density of the negatively charged acceptor-like states decreased. This is not consistent with the cases of GaN-cap/AlGaN/GaN Schottky diodes, which allow intentionally negative piezoelectric
charge on the top of AlGaN, and n-type Schottky diodes with a $p^+$-top layer to increase effective barrier height [116, 117].

![Conduction Band Diagram](image)

(a) As-deposited

(b) Annealed at 400 °C

$\phi_B < \phi_B' \Rightarrow E_{Fi} < E_{Fi}'$

Θ: Negatively-charged states

Θ: Neutralized states

Figure 4.7 Schematic conduction band diagram of as-deposited (a) and annealed (b) Ni/AlGaN/GaN Schottky diodes based on EBIC and $I-V$ results.

However, it can be explained by tunneling effects due to higher electric field within AlGaN barrier, resulting from the negatively-charged states of as-deposited one. On the
other hand, since the post-annealing causes the increase of net positive charge density near the Ni/AlGaN interface, the electric field and the resultant tunneling possibility decreases. Therefore, it is suggested that the effective barrier height ($\phi_{B, \text{eff}}$) after post-annealing increases because of less tunneling possibility due to reduced barrier electric field. It is also suggested that the Fermi level ($E_F'$) of annealed diodes is higher than $E_F$ of as-deposited ones. In other words, after annealing, difference between the Fermi level and conduction band edge of GaN at AlGaN/GaN interface ($E_{FiE}'$) is larger than before annealing, indicating that the 2DEG density increases after the post-annealing. Note that the energy levels of acceptor-like states in Figure 4.7 are hypothetical as a possible position. As discussed above, the energy levels are $\sim$38 meV and $\sim$0.31 eV, respectively, extracted from temperature-dependent transient characteristics when the bias is pulsed from ($V_{DSQ}$, $V_{GSQ}$) = (7 V, $-5$ V) as a pinch-off condition to ($V_{DS}$, $V_{GS}$) = (7 V, 0 V) [16]. One should note that a bias of ($V_{DS}$, $V_{GS}$) = (7 V, 0 V) on a transistor is equivalent to a reverse bias applied to a Schottky diode. Thus, trap energy levels at zero drain bias could be deeper than the extracted values as proposed by Mitrofanov et al. [23]. In addition, another emission time constant longer than 1 ms of the 20-min annealed HEMTs, which was not used for trap energy level extraction, is considered to be corresponding to even deeper traps. So, it is suggested that negatively-charged acceptor-like (or neutral donor-
like) states near Ni/AlGaN interface before annealing can become neutralized (or positive) after annealing, acting as deep traps. Note that another possible change of surface states is that shallow traps can become deep traps during annealing, leading to decrease and increase in the number of shallow and deep traps, respectively. In this case, these modified traps don’t affect EBIC images much as long as they keep staying at the same polarity or acting as positively charged donor-like states above the Fermi level. Overall, the net number of positive charge in the 20-min annealed HEMT is increased because of reduction of negatively-charged states. Again, the decrease in reverse leakage current of annealed Schottky diodes is due to the increase of deep trap’s density and decrease of shallow trap’s density, resulting in significant improvement of breakdown voltage.

The negatively-charged surface states, observed from EBIC images at zero bias, are considered to be acceptor-like states below the Fermi level. If other states like positively-ionized surface donor-like states are less affected by post-annealing or their polarity doesn’t change before and after annealing, 2DEG density at the AlGaN/GaN interface underneath Ni Schottky contact should be higher after the thermal reaction near the Ni/AlGaN interface. This is because the annealing process reduces negatively charged states for keeping charge neutrality based on the surface donor model. This can be
confirmed from static and dynamic characteristics of as-deposited and annealed AlGaN/GaN HEMTs as the following.

Figure 4.8 shows DC $I-V$ of as-deposited HEMT and 0.2 $\mu$s pulsed $I-V$s characteristics of as-deposited, and 10-min and 20-min annealed HEMTs at $V_{GS} = 0$ V using $(V_{DSQ}, V_{GSQ}) = (0$ V, $0$ V) as a quiescent bias point. The current level in 0.2-$\mu$s pulsed $I-V$ is higher using a quiescent bias of $(V_{DSQ}, V_{GSQ}) = (0$ V, $0$ V) than in DC $I-V$, meaning that there are more net positively-charged states at Ni/AlGaN interface under shorter pulse width conditions than under longer pulse widths or DC conditions. Saturation current levels in 0.2-$\mu$s pulsed $I-V$s of 10-min and 20-min annealed HEMTs are higher than as-deposited HEMT, indicating that post-annealing induced more positive states at the Ni/AlGaN interface. In other words, at equilibrium or zero bias condition in Schottky diodes, net number of positive charge and 2DEG density increase simultaneously after annealing at 400 °C. So, the Fermi level ($E_F$) is up-shifted after annealing. However, saturation current in DC $I-V$ of 20-min annealed HEMT is lower than that in 10-min annealed HEMT as shown in Figure 3.2 and 3.3 and similar to that in as-deposited one. Note that a drain bias of $V_{DS} > 0$ V at $V_{GS} = 0$ V is a reverse bias between the gate and the drain. Under such reverse bias condition, some electrons in DC or long-time pulsed $I-V$s can have enough time to be captured at trap sites near the
Ni/AlGaN interface, especially at drain-side gate edge in both as-deposited and annealed HEMTs. From this point-of-view, it is considered that 20-min annealed HEMT has more additional traps that are active under high $V_{DS}$ in DC or long-time pulsed $I-V$s in Figure 4.8(a) and Figure 3.3 than 10-min annealed one.

Figure 4.8 (a) DC $I-V$ of as-deposited HEMT and 0.2 pulsed $I-V$ characteristics of as-deposited, and 10-min and 20-min annealed HEMTs at $V_{GS} = 0$ V applying a quiescent bias of $(V_{DSQ}, V_{GSQ}) = (0$ V, $0$ V) and (b) pulse bias condition.

Note that 10-min annealed HEMTs showed less current dispersion between DC and pulsed $I-V$s, and improved RF/power performance [54]. Since the change of trap activity
by annealing is very sensitive to annealing temperature and time, post-annealing process
should be optimized for effective passivation for high performance AlGaN/GaN HEMTs.

4.3 X-ray photoemission spectroscopy (XPS) analysis on free AlGaN surface

The compositional change on free AlGaN surface in AlGaN/GaN Heterostructures without Schottky metal after annealing is examined using XPS to confirm whether unexpected reactions occur during annealing. Figure 4.9 shows Al 2p and Ga 3d XPS spectra of three different samples (as-grown, and 10-min / 20-min annealed). Al 2p and Ga 3d XPS spectra exhibited asymmetric shapes with shoulders near higher binding energies, corresponding to Al$_2$O$_3$ and Ga$_2$O$_3$ phases, respectively. Ga 3d spectra also had another broad shoulder (N 2S) at lower binding energies. Both spectra are consistent with Ref. [118]. After Al 2p and Ga 3d XPS spectra were decomposed into Al$_2$O$_3$ (~74.8 eV) and AlN (~73.7 eV) components, and Ga$_2$O$_3$ (~20.8 eV), GaN (~19.9 eV), and N 2s components as shown in Figure 4.10, the integrated intensity ratios of Al$_2$O$_3$ to AlN components and those of Ga$_2$O$_3$ to GaN components were compared for different samples [Figure 4.11(a)]. Note that the binding energies in parentheses are peak positions of the corresponding components. O 1s and N 1s intensity XPS spectra of three different samples were integrated, respectively. Note that N 1s XPS spectra decompose two components such as a strong component near N 1s peak and an unknown weak and
The integrated intensity ratios of O 1s to N 1s are compared, as shown in Figure 4.11(b). The XPS results indicate that unintentional oxidation occurred during the post-annealing. This can be explained by the thermodynamic data of the oxides and nitrides: Heat of formations of Al$_2$O$_3$, AlN, Ga$_2$O$_3$, and GaN at 298K is $-1678.2$, $-318.6$, $-1083.5$, and $-109.7$ kJ/mol, respectively [119]. The oxide layer on free AlGaN surface, especially near the edge of the Schottky contact, can prevent electron injection from the Schottky contact to surface states near the contact edge under reverse biasing conditions [14, 21]. The surface traps between the gate and the drain have been considered responsible for radio frequency (RF) current dispersion in AlGaN/GaN HEMTs [14].

Figure 4.9 XPS Al 2p and Ga 3d spectra with annealing time. Al-O (sapphire) and Ga-O (Ga$_2$O$_3$) bonds are located around 74.8 eV and 20.8 eV, respectively.
Figure 4.10 Raw and processed XPS O 1s, N 1s, Al 2p, and Ga 3d spectra of non-annealed AlGaN/GaN sample
Figure 4.11 (a) Integrated intensity ratios of oxide & nitride components in Al 2p & Ga 3d spectra and (b) integrated intensity ratios of O 1s & N 1s spectra with annealing time

4.4 Summary

Electrical behaviors at Ni/AlGaN interface have been investigated based on EBIC analysis to understand the post-gate annealing effects on interface states at Schottky metal/AGaN interface. The EBIC analysis results were correlated with PGA effects on trap activity in AlGaN/GaN HEMTs characterized in Chapter 3. The EBIC images showed that the post-annealing reduced the density of the electrically active states at the Schottky metal/AlGaN surface, leading to decrease of reverse leakage current, and J_S, and
increase of Schottky barrier height. We suggest that the post-annealing in AlGaN/GaN Schottky contacts induces passivation effect such as the reduction of the interface state density, contributing to the device performance improvement in AlGaN/GaN heterostructures. The methodologies for monitoring trapping activities in AlGaN/GaN HEMTs as described above will be applied for development of optimal device processing techniques with minimal trapping effects and a better electrical/thermal stability (i.e. surface passivation and dielectric layer insertion, surface plasma treatment, dry etching for mesa isolation, and PGA with different Schottky metals).
Chapter 5: Quantitative Characterization of Trapping effects in AlGaN/GaN HEMTs Using Pulsed $I-V$ Characteristics

5.1 Introduction

In this chapter, quantitative characterization of trapping effects on AlGaN/GaN HEMTs are illustrated based on a very short pulsed $I-V$ measurements using different quiescent biases (QBs) causing electron trapping over the AlGaN surface. Within very short pulse width, any activities of traps with emission/capture time constants of less than the applied pulse width are frozen. In addition, the short pulse allows us to realize constant temperature measurements. Trap activities in AlGaN/GaN HEMTs are dependent on QB points and pulse widths as discussed in the previous chapters. Active traps and their distributions in space and energy level are extremely difficult to identify using conventional methods such as time-dependent and temperature-dependent measurements. Even if some traps are identified under a certain characterization condition, it is questionable whether the observed traps are really active or not during the device operation. A better approach can be quantification of trap activity in $I-V$ characteristics in terms of device parameters for practical applications.

Various methods to extract device parameters such as threshold voltage, channel mobility, effective gate length, and mobility degradation factor have been reported for
device modeling of Si metal-oxide field effect transistors (MOFETS). [120-129] However, we cannot directly apply these Si-based conventional FET models for characterization of AlGaN/GaN HEMTs due to the trapping effects associated with the devices and their impact on carrier mobility along the channel. Although, recently, several attempts for device modeling in GaN-based HEMTs have been made [27, 58, 130, 131], the way that electrons are trapped under a specific QB point is not fully understood. So, accurate analysis of electron trapping in AlGaN/GaN HEMTs and its interpretation are challenging from the device physics point of view since the trapped charge distribution and energy levels are unknown.

In this work, we propose two simple methods to characterize AlGaN/GaN HEMTs in terms of device parameters based on pulsed $I-V$ characteristics and discuss correlation between trap activity and these parameters. In these models, impact of electron trapping on pulsed $I-V$ characteristics at different quiescent biases is incorporated into the effective gate length ($L_{G,\text{eff}}$) and average threshold voltage ($V_T$). The models are also based on pulsed $I-V$ measurement conditions where electron trapping and detrapping can be treated as static. The introduction of trapping-effect-incorporating device parameters gives a way for quantitative analysis of trapping effects as well as device modeling in AlGaN/GaN HEMTs. We demonstrate that the methods are very helpful for HEMT fabrication process monitoring and device reliability study.
In this chapter, using pulsed $I_D-V_{GS}$ characteristics with a very short pulse signal, two proposed methodologies for extraction of threshold voltage as well as other device parameters are developed: 1) zero-drain-bias output conductance method (Model 1) and 2) low-drain-voltage field method (Model 2). First, basic concepts of the models for the trap characterization are introduced together with short pulsed $I-V$ measurement condition for trap-free and trap-frozen $I-V$ characteristics. Then, the following subsections describe the current-voltage relationships in AlGaN/GaN HEMTs, basic ideas of both models, derivation of the model equations, and discussion about their modeling results, and validity.

### 5.2 Basic concept of AlGaN/GaN HEMT model

In general, electron trapping in AlGaN/GaN HEMTs can occur at different locations such as metal/AlGaN interface, the ungated AlGaN surface near the drain-side gate edge, AlGaN/GaN interface, and the buffer GaN layer during HEMT operation. So, separate analyses of trap activity at different places are challenging. In our models, electron trapping at the AlGaN/GaN interface after the bias pulses up from a quiescent bias to any measurement bias point is neglected since the measurement conditions described below ensure that there is little current flow under quiescent biases and negligible thermal effects at a very short pulse width compared with a long pulse
separation. But some electrons can be trapped in the GaN buffer at a QB point of the pinch-off condition. This electron trapping in the GaN buffer will be counted in the AlGaN surface in our analysis. So, our analyses focus on two locations of electron trapping effects: 1) Schottky metal/AlGaN interface and 2) the ungated AlGaN surface near source- and drain-side gate edges. The trapped charge at the Schottky metal/AlGaN interface and over the ungated AlGaN surface near the gate edge can be analyzed in terms of threshold voltage shift ($\Delta V_T$), effective gate length, and parasitic resistance change.

In addition, pulsed $I$–$V$ measurements is dependent on dynamics of carrier in devices. Normally, free electrons in the channel of AlGaN/GaN HEMTs are fast enough to response to any pulse signal, so they are less sensitive to the pulse width. However, electron emission and capture processes via traps depends on time constants of traps and pulse width, dynamics of electron transport via traps should be considered to analyze pulsed $I$–$V$ characteristics. Device temperature (i.e., power level) during HEMT operation also affects conduction of the HEMT. Thus, a very short pulse width and a long pulse duration are required to ensure the emission/capture processes are frozen and thermal effects are minimized.

The following subsections describe measurement conditions, HEMT model in presence of trapping effects, and current–voltage relationship in AlGaN/GaN HEMTs.
5.2.1 Quasi-static measurement conditions

As shown in Figure 5.1, the proposed models are based on two special pulse bias conditions for avoiding the dynamics of trapping effects and minimize thermal effects.

Figure 5.1 Schematic diagrams describing two special measurement conditions: (a) no electron trapping ($V_{trap} = 0$) and (b) the frozen trap charge ($V_{trap} = constant$), consisting of pulse conditions and conduction band diagrams in AlGaN HEMTs during pulsed $I-V$s using a very short pulse width [i.e., 0.2 $\mu$s pulse width, QB0 of ($V_{DSQ}$, $V_{GSQ}$) = (0 V, 0 V) for (a), and (b) QB2 (i.e., pinch-off condition) of ($V_{DSQ}$, $V_{GSQ}$) = (7 V, -6 V)].
Electron trapping is shown in the schematic conduction band diagrams at each measurement point in the cycle of applied drain and gate voltages with two specific QB conditions. Since a very short pulse width is applied, the pulsed I–V characteristics can be treated as quasi-static based on the following assumptions: 1) The number of traps with a capture time constant less than pulse width (PW) applied is negligible, meaning that when such a short pulse is applied, electron trapping within the applied PW for each measurement is neglected at QB0 of \((V_{DSQ}, V_{GSQ}) = (0 \text{ V}, 0 \text{ V})\) (Figure 5.1(a)). That is, there is no trapped charge; 2) The number of traps with an emission time constant less than PW applied is negligible, meaning that if a short pulse is applied, the trapped charge at a QB of sufficiently high reverse gate bias is frozen during pulsed I-V measurements (Figure 5.1(b)). That is, there is no emission of the trapped charge. Based on the above assumptions, change in \(V_T\) of a short pulse I–V characteristics between QB0 of \((V_{DSQ}, V_{GSQ}) = (0 \text{ V}, 0 \text{ V})\) and any QBs under which electrons are trapped (i.e. pinch-off QB ) is corresponding to \(V_T\) shift due to the density of trapped electrons \((n_{\text{trap,eff}})\). Once these two special bias conditions are established, \(n_{\text{trap,eff}} (=C_{\text{AlGaN}}V_{\text{trap}}/q)\) can be extracted from the threshold voltage shift \((\Delta V_T = V_{\text{trap}})\) in pulsed \(I_D-V_GS\) curves of an individual HEMT. In this work, using DIVA 210 and 265 dynamic I–V analyzers, a short pulse signal (0.2 \(\mu\text{s}\) with a pulse separation of 2 ms is applied to ensure that emission/capture processes of electrons by trap centers are affected not by each measurement point but by a QB
condition, leading to a constant $V_{trap}$ at a fixed QB. Various QB conditions, QB0 of $(V_{DSQ}, V_{GSQ}) = (0 \, \text{V}, 0 \, \text{V})$, QB1 of $(V_{DSQ}, V_{GSQ}) = (0 \, \text{V}, -6 \, \text{V})$, QB2 of $(V_{DSQ}, V_{GSQ}) = (7 \, \text{V}, -6 \, \text{V})$, and QB3 of $(V_{DSQ}, V_{GSQ}) = (0 \, \text{V}, -13 \, \text{V})$ are used for trap characterization. Figure 5.2 shows typical DC and pulsed $I_D-V_{DS}$ characteristics at $V_{GS} = 0 \, \text{V}$ of AlGaN/GaN HEMTs with QB0 and QB2 showing current dispersion between QB0 and QB2. QB0 is considered to be the same as equilibrium while QB1, QB2, and QB3 are pinch-off conditions (the threshold voltage of tested devices is about $\sim -4.4 \, \text{V}$). Under QB0, there is no electron capturing since HEMTs under test are at equilibrium. Each data point is measured 0.2 $\mu$s after the pulse changes from QB point to each bias voltage. If traps have a capture time constant of longer than 0.2 $\mu$s, there is no electron trapping at each bias point in QB0 case. On the other hand, some electrons are captured by trap centers under QB1, QB2, and QB3. If the electron emission time constant is longer than the pulse width (0.2 $\mu$s in this test), the response of the trapped charge to the pulse signal is negligible. Then, 0.2 $\mu$s after the pulse-up from QB1, QB2, or QB3 to each measurement point is too short for the captured electrons to emit. Thus, in these measurement conditions, the emission/capture processes of electrons by trap centers are affected by the quiescent bias conditions only, leading to a constant $V_{trap}$. As a result, the effective density of active traps at Schottky metal/AlGaN interface is independent of the applied bias for each measurement. More detailed discussion will be presented later in this chapter.
Figure 5.2 Current dispersions between DC and 0.2 μs pulsed $I_D-V_D$ characteristics at $V_{GS} = 0$ V using QB0 of $(V_{DSQ}, V_{GSQ}) = (0$ V, 0 V) and (b) QB2 of $(V_{DSQ}, V_{GSQ}) = (7$ V, $-6$ V) in typical AlGaN/GaN HEMTs.

5.2.2 HEMT model

The proposed device model is similar to that in conventional FETs. However, since AlGaN/GaN HEMTs suffers from trapping effects compared with more conventional FETs, here, we take a different way for extraction and definition of device parameters to AlGaN/GaN HEMTs.

Figure 5.3 shows schematic lateral energy band diagrams under different QBs with an equivalent circuit where $R_{Si}$ ($R_{Di}$) are the sum of contact resistance ($R_C$) and
constant source- (drain-) side resistance \( R_{Si,c} \) and \( R_{Di,c} \), and \( R_{STi} \) and \( R_{DTi} \) are field-dependent resistance of the trapped region below the ungated AlGaN surface in the source side and the drain side as in lightly-doped drain-source (LDD)-MOSFETs, and \( R_{CH} \) is the channel resistance of the intrinsic HEMTs. Note that \( R_{Si} \) and \( R_{Di} \) are used as constant parasitic series resistance for each QB\( i \) where \( i = 0, 1, 2, \) and \( 3 \), and field-dependent \( R_{STi} \) and \( R_{DTi} \) are combined into effective gate length \( (L_{Gi,eff}) \) term. Then, \( L_{Gi,eff} \) is accounted as the field-dependent or gate-modulated series resistance under both the gated and ungated trapped regions. In other words, \( L_{g,eff} \) defined as the length of the entire region where the channel conductance or resistance varies with applied biases, covers two trapped regions over the ungated AlGaN surface near the source-/drain-side gate edges and at Schottky metal/AlGaN interface. Note that, based on our definition, \( L_{g,eff} \) is not a physical but an electrical length in our model. Then, for QB0 where no electron trapping is expected, \( R_{S0} \) is equal to \( R_{D0} \) if HEMT device structures are symmetric. \( R_{Si} \) and \( R_{Di} \) for QB1, 2 and 3 are expected to be a little lower than \( R_{S0} \) and \( R_{D0} \) since field-dependent resistances due to the gate-edge electron trapping under QB1~3 are excluded in parasitic resistances at both source and drain side. Instead, \( L_{Gi,eff} \), combining both gate-voltage modulated channel and parasitic resistances, is expected to be longer than \( L_{G0,eff} \) for QB0 or a physical gate length \( (L_G = \sim 0.2 \ \mu m) \). In case of QB2, Electron-trapped region on the ungated surface in the drain-side is also expected to be more
extended toward drain contact than QB1 case because potential difference between gate and drain contacts under QB2 (Figure 5.3 (c)) are higher than under QB1 (Figure 5.3 (b)).

Figure 5.3 Schematic energy band diagrams of AlGaN/GaN HEMTs with an equivalent circuit using different QB points. i is an indicator corresponding to each bias condition.
In addition, since there are either no trapped region or symmetric trapped regions in both source-and drain-side gate edge at QB0, QB1, and QB3, respectively, $R_{S0}$ and $R_{Si,C}$ are equal to $R_{D0}$ and $R_{Di,C}$, respectively (i.e., $R_{Si} = R_{Di}$). However, since the QB2 bias results in asymmetric trapped regions in both source-and drain-side gate edge, $R_{S2,C}$ is not the same as $R_{D2,C}$. It should be noted that distribution of the trapped charge near the gate edge are affected mainly by $V_{GS}$ and $V_{GD}$. The spatial distribution of trapped electrons are similar in the source access region for both QB1 and QB2 since $V_{GS}$ values are same and both QBs are pinch-off (i.e., negligible potential variation from the source contact to the source-side border of the trapped region). So, $R_{S2}$ is equal to $R_{S1}$ and, similarly, and $R_{D2}$ equals $R_{D3}$ since $V_{GD}$ values are the same for both QB2 and QB3.

Generally, it is difficult to extract $V_T$, $L_{Gi,eff}$ and $R_{Si} (R_{Di})$ in DC $I-V$ characteristics in AlGaN/GaN HEMTs unlike Si MOSFET since such device parameters including trapping effects vary with QB bias and bias duration time. Figure 5.4 shows DC and pulsed $I_D-V_{GS}$ characteristics using different QBs indicating threshold voltage shift. Drain current near $V_T$ in DC $I_D-V_{GS}$ characteristics at a small fixed $V_{DS}$ is shifted toward that in 0.2 $\mu$s pulsed $I_D-V_{GS}$ with QB1 or QB2 while drain currents in both DC $I_D-V_{GS}$ and 0.2 $\mu$s pulsed $I_D-V_{GS}$ with QB0 are similar near $V_{GS} = 0$ V. This indicates that, in DC $I_D-V_{GS}$ characteristics, the density of active traps near the threshold voltage is larger than that near $V_{GS} = 0$ V.
Figure 5.4 DC $I_D-V_{GS}$ and 0.2 $\mu$s pulsed $I_D-V_{GS}$ characteristics at $V_{DS} = 0.2$ V using QB0 of $(V_{DSQ}, V_{GSQ}) = (0$ V, 0 V), QB1 of $(V_{DSQ}, V_{GSQ}) = (0$ V, $-6$ V), and QB2 of $(V_{DSQ}, V_{GSQ}) = (7$ V, $-6$ V), and QB3 of $(V_{DSQ}, V_{GSQ}) = (0$ V, $-13$ V) in a typical AlGaN/GaN HEMT.

Thus, it is considered that $V_{\text{trap,eff}}$ or $n_{\text{trap,eff}}$, and parasitic series resistances affected by electron trapping vary with gate bias. This is because, even if emission and capture rates of electrons are expected to be the same at each measurement bias in DC $I_D-V_{GS}$, these trapping/detrapping rates change with bias points. $V_{\text{trap,eff}}$ in DC $I_D-V_{GS}$ is not a function of measurement duration time since there is sufficient time for electrons to trap/emit in
DC \( I-V \) measurements. But it is still a function of \( V_{GS} \) and \( V_{DS} \). So, DC \( I_D-V_{GS} \) characteristics are not appropriate as a reference for trap characterization in AlGaN/GaN HEMTs. In addition, Pulsed \( I-V \) characteristics with long pulse width comparable with time constants of traps are not proper either because trap activity in this case depends on both bias points and measurement duration time. Therefore, 0.2 \( \mu \)s pulsed current–voltage curves (\( I_{D0}-V_{GS} \)) at QB0 is used as a reference since they are trap-free \( I_D-V_{GS} \) characteristics. It should be noted that \( V_{GS} \) near the threshold voltage in DC \( I-V \) is sufficiently high reverse bias for some electrons to trap under metal/AlGaN interface and over the un-gated AlGaN surface near the drain-side gate edge. Even at \( V_{GS} = 0 \) V, when \( V_{DS} \) is high enough, the gate-to-channel potential especially near the drain-side gate edge, is also sufficiently high enough for some electrons to be trapped. This is why we can observe the current dispersion in saturation regions between DC and 0.2 \( \mu \)s pulsed \( I_D-V_{DS} \) curves using QB0 together with thermal effects in DC \( I_D-V_{DS} \) characteristics as in Figure 5.2.

5.2.3 Current-Voltage relationship in AlGaN/GaN HEMTs in presence of trapping effects

Surface donor-like states have been considered as one of the sources for electrons in 2-dimensional quantum well at the AlGaN/GaN interface. When electron trapping is
involved in AlGaN/GaN heterostructures, the two-dimensional electron gas (2DEG) density as in Eq. (1–8) can be modified as:

\[ qn_s' = \sigma_{PZ} - qn_{trap} - C_{AlGaN} \left( \phi_B / q - \Delta E_C / q + E_{F_i0} / q \right) \]  

(5–1)

where \( \sigma_{PZ} \) is the polarization charge, \( n_{trap} \) is the density of traps participating in electron trapping, \( C_{AlGaN} \) is capacitance of the AlGaN barrier, \( \phi_B \) is the barrier height at AlGaN surface, \( \Delta E_C \) is the conduction band offset between AlGaN and GaN, and \( E_{F_i0} \) is the Fermi level with respect to the conduction band edge of GaN at the AlGaN/GaN interface.

Under the gradual channel approximation, the current-voltage \( (I–V) \) relationship in long-channel AlGaN/GaN HEMTs with series resistance and mobility degradation factor considered can be established using Eq. (5–1). In addition, there are negatively charged traps near the AlGaN surface, which are depending on the potential difference between the gate and the channel. So, the drain current in HEMTs can be expressed by

\[ I_D = \frac{\mu_{eff} W_G C_{AlGaN}}{L_{G,eff}} \left[ \left( V_{GS} - V_{T0} - V_{trap} - I_D R_S \right) - 1/2 \left[ V_{DS} - I_D \left( R_S + R_D \right) \right] \right] \times \left[ V_{DS} - I_D \left( R_S + R_D \right) \right] \]  

(5–2)

where \( \mu_{eff} \) is \( \mu_0 / [1 + \theta(V_{GS} - V_{T0} - V_{Trap} - I_D R_S)] \), \( \mu_0 \) is low field mobility, \( \theta \) is mobility degradation factor, \( V_{T0} = -C_{PZ} / C_{AlGaN} - \phi_B + \Delta E_C - E_{F_i0} / q \) is the threshold voltage at the condition that there is no electron trapping, \( V_{trap} \) is the threshold voltage shift due to electron trapping, \( L_{G,eff} \) is the sum of the physical gate length \( (L_G) \) and the
gate length variation ($\Delta L$) near the gate edge, $R_S$ and $R_D$ are source- and drain-access resistances, respectively.

As described above, we separated the two locations for electron trapping at metal/AlGaN interface under the gate and ungated AlGaN surface near the drain-side gate edge. The former trapping results in a threshold voltage shift toward a positive direction in current–voltage ($I-V$) characteristics of the HEMTs. The trap density ($n_{\text{trap}}$) can be characterized as the threshold voltage shift. The latter causes an increase of the parasitic series resistance, especially the drain-access resistance. However, it is hard to physically separate the parasitic series resistance and the channel resistance ($R_{CH}$) from device modeling of $I-V$ characteristics since both are field-dependent. Instead, an effective trap density ($n_{\text{trap,eff}}$) which can be considered as an average trap density at the metal/AlGaN interface and at the ungated AlGaN surface near the gate edge is introduced for electron trapping characterization. As illustrated above, the field-dependent parasitic resistance is incorporated into effective gate length ($L_{G,eff}$) to account for the density and spatial distribution of surface trapped electrons over the ungated AlGaN surface near both the source- and drain-side gate edges. The constant parasitic resistance to be extracted is expected to be smaller in the trap-frozen cases than in the trap-free condition since incorporation of the field-dependent resistance into $L_{G,eff}$ causes shortening of constant parasitic resistance region in length.
In addition, $V_{\text{trap}}$ or $n_{\text{trap}}$ is a function of $V_{GS}$, $V_{DS}$, and measurement duration time at each bias point in $I$--$V$ characteristics of AlGaN/GaN HEMTs. Or, in other words, $V_{GS}$ and $V_{DS}$ determine the trap activity such as rate and probability of the trapping/detrapping process, and spatial distribution of the active traps. In addition, the duration time after change of one bias point to another is a measure of how much time electrons are given to trap/emit as a response to change in the bias signal. Thus, by applying the measurement conditions and concepts described above, impact of trap activity can be evaluated by constant device parameters.

5.3 Models for AlGaN/GaN HEMTs including trapping effects

Various methods for device characterization of long/short gate transistors have been reported in Si technology [122, 125-128]. To extract threshold voltage ($V_T$) in long-channel AlGaN/GaN HEMTs, some conventional methods as in Si MOSFETs can be utilized in $I$--$V$ characteristics: 1) linear extrapolation at maximum transconductance ($g_{m,\text{max}}$) point in the linear region (peak $g_m$ method) using Eq. (5–3) and 2) the De la Moneda method with Eq. (5–4) [121, 129],

\[
V_T = V_{GSi} - \frac{V_{DS}}{2} + \frac{1 - \sqrt{1 + 4K_{0,\text{max}}R_{SD}(V_{GS,\text{max}} - V_{GSi})}}{2K_{0,\text{max}}R_{SD}} \quad (5-3)
\]
\[
\frac{I_D}{\sqrt{g_m}} = \sqrt{K_0V_{DS}(V_{GS} - V_T)}
\]  \quad (5-4)

where \(V_{GSI}\) is y-intercept of the linear extrapolation at the peak \(g_m\) point of \(I_D - V_{GS}\) curves, \(K_{0,\text{max}}\) and \(V_{GS,\text{max}}\) are values at the peak \(g_m\) point, \(R_{SD}\) is the sum of the source/drain parasitic series resistances, \(V_{DS}\) is a fixed small \(V_{DS}\) (i.e., \(V_{GS} - V_T \gg V_{DS}\) or \(V_{GS} - V_T \gg I_D R_S\)), and \(K_0\) is \(W_G \mu_0 C_{AlGaN}/L_{G,\text{eff}}\). Even if series resistance is considered for both methods, lateral field effect is not included. In Eq. (5–3), \(R_{SD}\) and \(L_{G,\text{eff}}\) should be known and De la Moneda method is also not good for a noisy data since the measured \(I_D - V_{GS}\) data have to be differentiated. So, both methods are not proper for characterization of pulsed \(I_D - V_{GS}\) with trapping effects since AlGaN/GaN HEMTs analyzed in this work has short gate (~0.2 \(\mu\)m), \(R_{SD}\) and \(L_{G,\text{eff}}\) are unknown, and pulsed \(I_D - V_{GS}\) data are noisy.

Normally, the short channel effects shift \(V_T\) in n-channel Si-MOSFETs toward the negative direction due to the charge sharing near the channel edge. Similarly, those effects change \(V_T\) in AlGaN/GaN HEMTs to more negative values caused by “gate-fringing effects” although these results are based on DC \(I-V\) characteristics and without consideration of lateral field effect for short gates [132]. To extract more accurate device parameters in short channel devices, generally, a long channel device and several short channel ones with different gate lengths are analyzed with 2-D device simulators. Alternatively, “Shift and ratio (SR) method [124, 132]” is applied to determine threshold
voltage and effective gate length for short-channel devices. SR method can be applied for $V_T$ extraction of short-channel HEMTs with different gate lengths and the same width.

$$R_m = R_T + L_{G,eff} f(V_{GS} - V_T) \quad (5-5)$$

where $R_m = V_{DS}/I_D$ is the total resistance of FETs, $R_T$ is the sum of source/drain parasitic series resistances, and $f(V_{GS} - V_T) = 1/[ \mu_{eff} C_{AlGaN} W G(V_{GS} - V_T - 1/2 V_{DS})]$ is a general function of $(V_{GS} - V_T)$ [125, 133]. In this method, it is considered that $\mu_{eff}$ as a common function of $(V_{GS} - V_T)$ is not dependent on the channel length but $V_T$ changes with the channel length due to the short-channel effects. Originally, this method was utilized for at least two different Si MOSFETs with long and short gates to extract $V_T$ and $L_{G,eff}$ for short channel devices. We can apply this concept for AlGaN/GaN HEMTs using different QBs such as QB0, QB1, and QB3. Note that this method requires the same source and drain parasitic resistances or a very small difference between them, so it may not be applied to QB2 case. By differentiating Eq. (5–5) with respect to $V_{GS}$ as in SR method, its derivative can be expressed as:

$$S_i = \frac{dR_{m,i}}{dV_{GS}} = L_{G,i,eff} \frac{d[f(V_{GS} - V_{T,i})]}{dV_{GS}} \quad (5-6)$$

where $i$ is an indicator of each QB condition. When $S_0$ for QB0 is compared with other $S_i$ for QB1 and QB3, either $S_0$ or $S_i$ has to be shifted by $\delta$ so that the shifted derivative of $f(V_{GS} - V_{T0} - \delta)$ for QB0 become equal to the derivative of $f(V_{GS} - V_{Ti})$ for QB1 and QB2.
Then, $\delta$ is the difference in $V_T$ between QB0 and QBi cases and the ratio of $S_0$ to the shifted $S_0$ is $L_{G1,eff}/L_{G0,eff}$. The SR method will be discussed in part of Model 2 in Section 5.3.2. In this work, we focus on single geometry HEMTs for device parameters extraction.

The basic concepts and characterization conditions of two proposed methods are described to analyze effects of electron trapping under the gate and over the ungated AlGaN surface near the drain-side gate in AlGaN/GaN HEMTs on current-voltage ($I-V$) characteristics. The methodology to quantitatively examine the trapping effects requires the realization of trap-free and trap-frozen $I-V$ measurements as illustrated above. Then, device parameters extracted from these $I-V$ characteristics are compared to evaluate trapping effects on AlGaN/GaN HEMT performance. First, Model 1 of zero drain bias output conductance method can be used without knowing source/drain parasitic resistances but is a noise-producing process due to differentiation of data. Model 2 of low drain bias mobility method is a less-noisy process but the extracted parameters may not be physical parameters, again, because single geometry HEMTs are analyzed. Both simple methods will be introduced and examined in the following subsections.
5.3.1 Model 1: Zero drain bias output conductance method

Basic concepts

This method is developed to extract $V_T$ and $K_0$ ($= C_{AlGaN} \mu_0 W_G/L_{G,eff}$) from a plot of $g_D (= \partial I_D/\partial V_{DS})$ at $V_{DS} = 0$ with respect to $V_{GS}$. In this case, source and drain parasitic resistances don’t have to be known since series resistance effects is ruled out due to negligible $I_D$ at $V_{DS} = 0$. In addition, since we are dealing with near-zero drain bias, lateral field effect is negligible even in the short-channel HEMTs. A drawback of this method is that this is a noise producing process since differentiation of $I_D$ with respect to $V_{DS}$ is required. The resolution of dynamic analyzer for pulsed $I–V$ measurements also limits the accuracy of this method.

Derivation of the model equations and modeling results

To derive the model equations, we start with a general $I–V$ relationship with parasitic series resistance and lateral field effects as in Eq. (5–7):

$$I_{Di} = \frac{C_{AlGaN} \mu W_G}{L_{G,eff}} \left[ V_{GDi} - 1/2 \left[ V_{DS} - I_{Di} (R_{Di} - R_{Si}) \right] \right]$$

$$= \frac{K_{Oi} \left[ V_{GDi} - 1/2 \left[ V_{DS} - I_{Di} (R_{Di} - R_{Si}) \right] \right] \left[ V_{DS} - I_{Di} R_{Ti} \right]}{\left[ 1 + \theta (V_{GDi} - I_{Di} R_{Si}) \right] \left[ 1 + \eta (V_{DS} - I_{Di} R_{Ti}) \right]} \quad (5–7)$$
where \( \mu = \frac{\mu_0}{\left[1 + \theta_i (V_{GTi} - I_{D0}R_{Sij})\right]\left[1 + \eta_i (V_{DSi} - I_{Di}R_{Tij})\right]} \), \( K_0 = C_{AiGaN}\mu_0 W_G/L_{Gi,eff} \), \( \eta_i = 1/(L_{Gi,eff}E_C) \), \( E_C \) is a critical field for velocity saturation, and the other parameters have the same definition as described above. Note that the expression of \( \mu \) is the same as an empirical form of the carrier mobility in Si MOSFETs [133]. Since we consider \( I_D-V_{DS} \) near \( V_{DS} = 0 \) V, the lateral field effect and its derivative are negligible. Then, by differentiating Eq. (5–7), the following model equation can be deduced in a form of a rational function:

\[
\frac{\partial I_D}{\partial V_{DS} \text{ at } V_{DS} = 0 \text{ V}} = \frac{K_{0i}/[K_{0i}R_{Ti} + \theta_i] V_{GTi} V_{GSi} + b_i V_{GSi} + a_i}{V_{GSi} + a_i} (5-8)
\]

where \( a_i = 1/[K_{0i}R_{Ti} + \theta_i] - V_{Ti} \), \( b_i = -K_{0i}V_{Ti}/[K_{0i}R_{Ti} + \theta_i] \), and \( c_i = K_{0i}/[K_{0i}R_{Ti} + \theta_i] \) [See Appendix A.1]. First, the derivative of \( I_D (g_D = \partial I_D/\partial V_{DS}) \) with respect to \( V_{DS} \) at \( V_{DS} = 0 \) V is extracted at each \( V_{GS} \). Second, \( g_D \) at \( V_{DS} = 0 \) V is plotted as a function of \( V_{GS} \). Finally, a non-linear curve fitting of \( (g_D, V_{GS}) \) to Eq. (5–8). \( V_{Ti} \) and \( K_{0i} \) are determined by the fitting parameters: \( V_{Ti} = -b_i/c_i \) and \( K_{0i} = c_i / [a_i + V_{Ti}] \).

Figure 5.5 shows a plot of \( g_D \) at \( V_{DS} = 0.035 \) V as a function of \( V_{GS} \) for two different HEMTs using QB0 and QB2 with non-linear fitting curves. Table 5.1 lists the fitted parameters and the extracted \( V_{Ti} \) and \( K_{0i} \) for QB0 and QB2. Based on this model, difference in trapping effects between QB0 and QB2 can be interpreted in terms of \( V_{Ti} \), \( K_{0i} \), \( \mu_0 \), and \( L_{Gi,eff} \) assuming \( L_{G0,eff} \) for QB0 equals the physical gate length \( L_G = \sim 0.2 \) \( \mu \)m.
$C_{AlGaN}$ is $\sim 3.6 \times 10^{-7}$ F/cm$^2$ using $d_{AlGaN} = 23$ nm and $\varepsilon(x) = -0.5x + 9.5$ where $x$ is the Al fraction in AlGaN [78]. The effective trap density ($n_{\text{trap,eff}}$) is calculated by $C_{AlGaN}\Delta V$ where $\Delta V$ is $V_T$ difference between QB0 and QB2. HEMT 1 showing less electron trapping as in Figure 5.2 (a) has less $\Delta V$ between QB0 and QB2, and less $n_{\text{trap,eff}}$ for QB2, and shorter effective gate length than HEMT 2, which has larger current dispersion. In addition, once AlGaN/GaN HEMTs with different gate lengths are prepared, more accurate low field mobility ($\mu_0$) and effective gate length ($L_{Gi,\text{eff}}$) for each QB can be extracted from the slope and $x$-intercept ($\Delta L$) of a plot of $K_{0i}$ with respect to different physical gate lengths for each QB. For example, $L_{G0,\text{eff}}$ for QB0 is the sum of the physical gate length ($L_G$) and $\Delta L$. and the other $L_{Gi,\text{eff}}$ is calculated by multiplying the ratio of $K_{00}$ to $K_{0i}$ by $L_{G0,\text{eff}}$ assuming $\mu_0$ is constant for all QBs. Note that $\mu_0$ does not have to be a constant, so different $\mu_0$ values for each QB can be also extracted from a plot of $K_{0i}$ with respect to different physical gate lengths for each QB. This is because $\mu_0$ value for each QB can reflect gate-voltage modulated parasitic resistance effect when it is extracted.
Figure 5.5 Measured and fitted $g_D$ at $V_{DS} \sim 0.035\text{V}$ with respect to $V_{GS}$ of HEMT 1 (a) and HEMT 2 (b).

Table 5.1 List of the fitting parameters, and the extracted device parameters of HEMT 1 and HEMT 2 assuming $L_{G0,\text{eff}}$ for QB0 is equal to the physical gate length ($L_G$) of $\sim 0.2 \mu\text{m}$, $C_{\text{AlGaN}} = 3.6 \times 10^{-7} \text{C/cm}^2$, and $qn_{\text{trap,eff}} = C_{\text{AlGaN}} \Delta V$.

<table>
<thead>
<tr>
<th></th>
<th>$a_i$ (V)</th>
<th>$b_i$ (A)</th>
<th>$c_i$ (S)</th>
<th>$V_T$ (V)</th>
<th>$n_{\text{trap,eff}}$ (#/cm2)</th>
<th>$K_0$ (A/V²)</th>
<th>$\mu_0$ (cm²/Vs)</th>
<th>$L_{G2,\text{eff}} / L_{G0,\text{eff}}$</th>
</tr>
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<tr>
<td>HEMT 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>QB0</td>
<td>$\sim 5.12$</td>
<td>$\sim 0.236$</td>
<td>$\sim 0.0536$</td>
<td>$\sim 4.41$</td>
<td></td>
<td>$\sim 0.0747$</td>
<td>$\sim 415$</td>
<td></td>
</tr>
<tr>
<td>QB2</td>
<td>$\sim 4.89$</td>
<td>$\sim 0.170$</td>
<td>$\sim 0.0406$</td>
<td>$\sim 4.18$</td>
<td>$\sim 5.1 \times 10^{11}$</td>
<td>$\sim 0.0572$</td>
<td>$\sim 415$</td>
<td>$\sim 1.3$</td>
</tr>
<tr>
<td>HEMT 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>QB0</td>
<td>$\sim 5.00$</td>
<td>$\sim 0.224$</td>
<td>$\sim 0.0489$</td>
<td>$\sim 4.58$</td>
<td></td>
<td>$\sim 0.117$</td>
<td>$\sim 651$</td>
<td></td>
</tr>
<tr>
<td>QB2</td>
<td>$\sim 4.29$</td>
<td>$\sim 0.116$</td>
<td>$\sim 0.0309$</td>
<td>$\sim 3.77$</td>
<td>$\sim 1.9 \times 10^{12}$</td>
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<td>$\sim 651$</td>
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</table>

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5.3.2 Model 2: Low drain bias mobility method

Basic concepts

Model 1 allows us to extract physical device parameters without knowing parasitic series resistance values but it requires differentiation, which leads to noisy extracted parameters. To avoid the noise produced in Model 1, a new concept is introduced such as low-drain-bias mobility \( \mu_{0,\text{LOW}} \) and mobility degradation factor \( \theta_{i,\text{LOW}} \), which are similar to low-field mobility \( \mu_0 \) and mobility degradation factor \( \theta_i \) in the long-channel devices. \( \mu_{0,\text{LOW}} \) and \( \theta_{i,\text{LOW}} \) include lateral field effect at a low drain voltage and the mobility \( \mu(F) \) at high electrical field can be still considered as a function of lateral electric field \( F \) in an empirical form of Eq. (5–9) [133, 134] while \( \mu_0 \) and \( \theta_i \) do not count any lateral field effect in short channel devices.

\[
\mu(F) = \frac{\mu_{0,\text{LOW}}}{\left[1 + \theta_{i,\text{LOW}} (V_{GTi} - I_{Di} R_{Si}) \right] \left[1 + \left( \frac{F_{\text{lateral}}}{F_{C}} \right)^n \right]}^{1/n}
\]

\[
\mu_{0,\text{LOW}} = \frac{\mu_{0,\text{LOW}}}{\left[1 + \theta_{i,\text{LOW}} (V_{GTi} - I_{Di} R_{Si}) \left[1 + \left\{ \eta_i (V_{DS} - I_{Di} R_{Ti}) \right\}^n \right]^{1/n} \right]}
\]  

(5–9)

In Model 2, \( [1 + \eta_i (V_{DS,\text{LOW}} - I_{Di} R_{Ti})]^n \) is assumed to be a unity at a specific fixed low drain voltage \( V_{DS,\text{LOW}} \) as a reference. But this doesn’t mean there is no lateral field effect
at $V_{DS,LOW}$. Both $\mu_{0,LOW}$ and $\theta_{i,LOW}$ include the lateral field effect at $V_{DS,LOW}$. This is because the lateral electric field is high even at $V_{DS,LOW}$ (i.e., $F_{lateral} = \sim 10$ kV/cm at $V_{DS,LOW} = 0.2$ V for a 0.2 μm gate device). In addition, $[1+ \eta(V_{DS} - I_{Di}R_{T})^{n}]^{1/n}$ should be considered at $V_{DS} > V_{DS,LOW}$ for modeling of $I–V$ characteristics. In Model 2, differentiation is not required for extracting device parameters since $I_{D}–V_{GS}$ data is directly utilized for curve fitting.

**Derivation of the model equations**

A current–voltage relationship in Model 2 is the same form as in Eq. (5–7) but $K_{0i}$, $\mu_{0i}$, and $\theta_{i}$ are replaced by $K_{0i,LOW}$, $\mu_{0i,LOW}$ and $\theta_{i,LOW}$. The current–voltage relationship at $V_{DS} = V_{DS,LOW}$ for QBi can be reduced to:

$$I_{Di} = \frac{K_{0i,LOW}(V_{GSI} - V_{Ti} - 1/2V_{DS})V_{DS}}{[\theta_{i,LOW} + K_{0i,LOW}R_{Ti}(V_{GSI} - V_{Ti}) + 1 - K_{0i,LOW}V_{DS}R_{Di}]} = \frac{c_{i}V_{GSI} + b_{i}}{V_{GSI} + a_{i}}$$

$$A_{i} = \theta_{i,LOW} + K_{0i,LOW}R_{Ti}, \quad a_{i} = -V_{Ti} + 1 - K_{0i,LOW}V_{DS}R_{Di}, \quad b_{i} = -K_{0i,LOW}(V_{Ti} + 1/2V_{DS})V_{DS},$$

and $c_{i} = \frac{K_{0i,LOW}V_{DS}}{A_{i}}$

where $K_{0i,LOW}$ is $\mu_{0i,LOW}C_{AlGaN}W_{G}/L_{G0,eff}$. Eq. (5–10) is based on the assumption that Eq. (5–11) is valid.
The left side of Eq. (5–11) is the second-order term in the quadratic equation of Eq. (5–7) at $V_{DS,LOW}$ (i.e., $[1+ \{ \eta(V_{DS,LOW} - I_{DSRT}) \}^{1/n}]^{1/n}$). So, the effect of the second-order $I_D$ due to the intrinsic drain/gate voltage and effective mobility terms is neglected in Model 2. This assumption will be verified after extraction of device parameters and a more detailed derivation is shown in Appendix A.2. Eq. (5–10) is a form of a rational function as in $I_{Di} = (c_iV_{GSi} + b_i)/(V_{GSi} + a_i)$ similar to non-linear equation for Si MOSFET device modeling [127, 135]. $V_{Ti}$ can be extracted by doing non-linear fitting of Eq. (5–10) to the measured $I_{DS=VG}$ data. $V_{Ti}$ is equal to $(-b_i/c_i-1/2V_{DS,LOW})$. The effect of the second-order $I_D$ due to the intrinsic drain/gate voltage and effective mobility terms is neglected under the assumption of Eq. (5–11). To roughly check the validity of the assumption that effects of the second-order $I_{D0}$ is negligible for QB0, we presume that $\mu_{0,LOW}$ is $\sim$1000 cm/Vs, $C_{AlGaN}$ is $\sim$3.6$\times$10$^{-7}$ F/cm$^2$, $W_G$ is 100 $\mu$m and $L_{G0,eff}$ is $\sim$0.2 $\mu$m which is the physical gate length. Then, a roughly-estimated $K_{0,LOW}$ is $\sim$0.180 A/V$^2$. At this moment, $\theta_{0,LOW}$ is unknown but is expected to be similar to that in Si MOSFETs (0.01 $\sim$ 1 V$^{-1}$) [126, 127]. For example, if $R_{S0} (= R_{D0}) = -9.5 \Omega$ estimated from TLM measurement results is used with $\theta_{0,LOW}/K_{0,LOW} = 1$, the second-order term of $I_{D0}$ in Eq. (5–7) or the
left hand of Eq. (5-11) for HEMT1 is \((\theta_{0,\text{LOW}} / K_{0,\text{LOW}}) R_{S0} I_{D0}^2 = 3 \times 10^{-4} \text{ V}^2 \) to \(9 \times 10^{-4} \text{ V}^2\) in the \(V_{GT}\) range of 1 V to 4.5 V, while the right hand of Eq. (5-11) is \((V_{GT} - 1/2 V_{DS,\text{LOW}}) V_{DS,\text{LOW}} = 0.18\) to 0.88 \text{ V}^2. Then, the left side is much lower by three orders of magnitude than the right side. This indicates that the assumption that the second-order \(I_{D0}\) term is negligible is reasonable for QB0. Therefore, the effect of the mobility degradation factor in the second order term of \(I_{D0}\) as seen in Eq. (5-7) will be neglected to extract \(V_T\) at \(V_{DS,\text{LOW}}\) for QB0. Once \(V_T\) is extracted, the validity of Eq. (5-11) will be demonstrated later in this section by showing \(\theta_{0,\text{LOW}} / K_{0,\text{LOW}} < 3\) after \(\theta_{0,\text{LOW}}\) and \(K_{0,\text{LOW}}\) extraction from a plot of the transistor gain \((K)\) against \(V_{GT}\) or \((V_{GT} - I_{D0} R_{S0})\) with differently assumed \(R_{S0}\) values. Note that \(R_{TO} = R_{S0} + R_{D0}\) cannot be extracted in this work since our AlGaN/GaN HEMTs to be analyzed have a single gate length only, so \(R_{S0}\) values for the above verification will be based on measurement results of transfer length method (TLM) test structures in the same die of HEMTs.

**Device parameter extraction procedure**

This section illustrates the procedure to extract constant \(V_{T}, R_{Si}, R_{Di}, \text{ and } L_{Gi,\text{eff}}\) for different QBs. At this moment, we cannot extract \(R_{Si}\) and \(R_{Di}\) since we don’t have HEMTs with different gate lengths and the same spacing between gate and source/drain. However, a way to extract \(R_{Si}\) and \(R_{Di}\) are described and different \(R_{Si}\) and \(R_{Di}\) values are
used for model verification. In this work, $V_T$ is extracted for an appropriate wide range of $I_D-V_{GS}$ data by performing non-linear curve fitting based on non-linear optimization with iterative linear regression. This is meaningful because a procedure to extract other device parameters is illustrated. The following subsections describe $V_{Ti}$, $L_{Gi,eff}$, $K_{\theta_i,LOW}$, $\mu_{0i,LOW}$, and $\theta_{i,LOW}$ for QBi.

Step 1) $V_T$ extraction: Theoretically, at least three data points of $(I_D, V_{GS})$ are required to get a set of three fitting parameters and extract device parameters as introduced in Ref. [135]. However, a wide range of $V_{GS}$ is used to minimize deviation from noise of the measurement data and extract more accurate device parameters. Ideally, the range of $V_{GS}$ in the deep linear region has to be chosen to make sure that transverse field along the channel is constant (i.e., $V_{GS} - V_T \gg V_{DS,LOW}$). In this work, a fixed $V_{DS,LOW}$ of 0.2 V was applied for pulsed $I_D-V_{GS}$ characteristics since $I_D-V_{GS}$ data at a $V_{DS}$ of less than 0.2 V are a little noisy. So, the measured data within $(V_{GS} - V_T) = 0 \text{ V} \sim 0.3 \text{ V}$ were filtered out while the data within $(V_{GS} - V_T) > 0.3 \text{ V}$ need to be analyzed for a more accurate extraction of $V_T$. Non-linear curve fitting of Eq. (5–10) to the measured $I_{D0}-V_{GS}$ of two selected HEMTs for QB0 is performed as shown in Figure. 5.6. The threshold voltages of HEMT 1 with less current dispersion and HEMT 2 with more current dispersion are $-4.37 \text{ V}$ and $-4.49 \text{ V}$, respectively, for QB0. Table 5.2 lists all the fitted parameters, $V_{Ti}$, $\Delta V_{T}$, and $n_{trap,eff}$. 

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Figure 5.6 0.2 μs pulsed $I_{D0}$-$V_{GS}$ characteristics at $V_{DS,LOW} = 0.2$ V using QB1 of ($V_{DSQ}$, $V_{GSQ}$) = (0 V, 0 V) of HEMT1 [(a)] and HEMT 2 [(b)] Square symbol and solid line are corresponding to measured and fitted data, respectively.

Table 5.2 List of the fitting parameters, and the extracted device parameters of HEMT 1 and HEMT 2 assuming $L_{G0,eff}$ for QB0 is equal to the physical gate length ($L_G$) of ~0.2 μm, $C_{AlGaN} = 3.6 \times 10^{-7}$ C/cm$^2$, and $q_n n_{trap,eff} = C_{AlGaN} \Delta V$. 1 and 2 in the table are corresponding to HEMT 1 and HEMT 2, respectively.

<table>
<thead>
<tr>
<th></th>
<th>$a_i$ (V)</th>
<th>$b_i$ ($1 \times 10^{-3}$V·A)</th>
<th>$c_i$ ($1 \times 10^{-3}$A)</th>
<th>$V_T$ (V)</th>
<th>$\Delta V_T$ (V)</th>
<th>$n_{trap,eff}$ ($1 \times 10^{11}$/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>QB1</td>
<td>-5.02</td>
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<td>-3.78</td>
<td>-3.86</td>
<td>-8.95</td>
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</tr>
<tr>
<td>QB2</td>
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<td>-3.22</td>
<td>-8.95</td>
<td>-7.79</td>
</tr>
<tr>
<td>QB3</td>
<td>-5.10</td>
<td>-6.42</td>
<td>-3.29</td>
<td>-3.18</td>
<td>-8.22</td>
<td>-7.95</td>
</tr>
</tbody>
</table>
Step 2) Other device parameter extraction: The way to extract $\mu_{i,LOW}$, $R_{Ti}$, $\theta_{i,LOW}$, and $L_{Gi,eff}$ is similar to that in Si MOSFETS like Suicui Johnston (SJ) [120] method or CMP method [127]. Note that HEMTs with equal gate widths and different gate lengths have to be analyzed to extract those device parameters. Eq. (5–10) for QBi can be rewritten in the following form as in SJ method:

$$R_{mi}(V_{GTi} - 1/2 V_{DS,LOW}) = \left( \frac{\theta_{i,LOW}}{K_{0i,LOW}} + R_{Ti} \right) V_{GTi} + \frac{1}{K_{0i,LOW}} V_{DS,LOW} R_{Di} \quad (5–12)$$

where $R_{mi}$ is $V_{DS,LOW}/I_{Di}$, $V_{GTi}$ is $(V_{GSi} - V_{Ti})$, $1/K_{0i,LOW}$ is $L_{Gi,eff}/\mu_{0i,LOW}C_{AlGaN}W$, and $L_{Gi,eff}$ is the sum of the physical gate length ($L_G = \sim 0.2 \mu m$) and gate length variation ($\Delta L_i$). Note that $R_{Si}$ is equal to $R_{Di}$ for QB0, QB1, and QB3 but $R_{S2}$ and $R_{D2}$ for QB2 are different due to asymmetric trapping effect near source-/drain-side edges. Eq. (5–12) can be applicable for QB2 case as long as the assumption of Eq. (5–11) is valid. Once $V_{Ti}$ is extracted, the slope ($\theta_{i,LOW}/K_{0i,LOW} + R_{Ti}$) and the intercept ($1/K_{0i,LOW} - V_{DS,LOW} R_{Di}$) in the ordinate are determined from a plot of $R_{mi}$ ($V_{GTi} - 1/2 V_{DS,LOW}$) versus $V_{GTi}$ for each individual HEMT as shown in Figure 5.7. Then, $\mu_{0i,LOW}$ and $\theta_{i,LOW}$ can be extracted from the slopes in plots of $(1/K_{0i,LOW} - V_{DS,LOW} R_{Di})$ versus gate length and $(\theta_{i,LOW}/K_{0i,LOW} + R_{Ti})$ versus gate length. $R_{T0}$ and $\Delta L$ can be also extracted from the intercepts in the ordinate of both plots. One should note that, unlike the original SJ method, the third term

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in the right hand of Eq. (5–12) contains $V_{DS,LOW} R_{Di}$, which is estimated to be more than 19% of $1/K_{0,LOW}$ for QB0 as will be shown later in this section. Thus, $V_{DS,LOW} R_{Di}$ has to be included for more accurate analysis. Alternatively, $a_i$ and $c_i$ in the fitting parameters of Eq. (5–10) can be directly used to extract device parameters. $a_i$ and $c_i$ expressions can be rewritten as $V_{DS,LOW}/c_i = \theta_{i,LOW}/K_{0,LOW} + R_{Ti}$ and $(a_i + V_{Ti}) = (c_i/V_{DS,LOW})/K_{0,LOW} - c_i R_{Di}$. $\mu_{0,LOW}$ and $\theta_{i,LOW}$ can be extracted from the slopes in plots of $(V_{DS,LOW}/c_i)$ and $(a_i + V_{Ti})$ against gate length. $R_{Ti}$ and $\Delta L_i$ can also be calculated from the intercepts in the ordinate of both plots.

![Figure 5.7 Modified SJ plot for each QB of HEMT 1 and HEMT 2.](image)

Figure 5.7 Modified SJ plot for each QB of HEMT 1 and HEMT 2.
Since the gate lengths of our HEMTs are equal, \( R_{Ti} \) or \( 2R_{Si} (=2R_{Di}) \) for QB0, 1, and 3 cannot be extracted from the method described above. Instead, we used three different parasitic series resistance values to check whether our assumption of Eq. (5–11) is valid. Figure 5.8 shows a plot of \( K (= \mu_{eff}C_{AlGaNG/Geff}) \) as a function of \( V_{GT0} \) with different \( R_{So} \) values for HEMT 1 and HEMT 2 for QB0 to extract \( K_{00,LOW} \) and \( \theta_{0,LOW} \). Table 5.3 lists \( R_{So}, K_{00,LOW} \) and \( \theta_{0,LOW} \) for the \( V_{GT0} \) range of 1 V to 4.5 V, and ratios of \( R_{So} \times (\theta_{0,LOW} / K_{00,LOW})I_{D0}^2 \) and \( V_{DS,LOW} (V_{GT0} − 1/2 V_{DS,LOW}) \) at \( V_{GS} = 0 \) V for HEMT 1 and 2. The ratios with three different \( R_{So} \) values are smaller than \( \sim 2 \times 10^{-3} \) for both HEMT1 and HEMT2, demonstrating that the assumption of Eq. (5–11) is valid for QB0. In addition, \( K_{00,LOW} \) is less sensitive to the series resistance for QB0 than \( \theta_{0,LOW} \). For QB2, Eq. (5–10) and (5–12) can be applicable if difference between \( R_{S2} \) and \( R_{D2} \) is small enough to keep the assumption of Eq. (5–11) valid. However, if electron trapping near the drain-side gate edge is much more than that near the source-side gate edge or extension of the electron trapped region toward the drain contact is than that toward the source contact, difference between \( R_{S2} \) and \( R_{D2} \) will be large. So, in this case, \( 1/2(R_{Si}^2 − R_{Di}^2)I_{Di}^2 \) term at the left side of Eq. (5–11) should be added for the analysis of current-voltage characteristics. Note that the estimated \( K_{00,LOW} \) values (\( \sim 0.111 \sim 0.114 \) A/V^2 for HEMT1 and \( \sim 0.139 \sim 0.143 \) A/V^2 for HEMT 2) are smaller than the calculated \( K_{0}(\sim 0.18 \) A/V^2) with \( \mu_0 = 1000 \) cm-
$V_{GS}$ and $L_{G0,eff}=0.2 \, \mu m$. This may be because $\mu_{0i,LOW}$ is lower due to the lateral electric field effect than $\mu_0 = 1000 \, cm^2/Vs$ or/and $L_{G0,eff}$ is longer than the physical length due to gate-edge effects.

Figure 5.8 Plots of $K \left( = \mu_{eff} C_{AlGaN} W_{g}/L_{G0,eff} \right)$ with respect to $V_{GT}$ with different $R_{S0}$ values for HEMT 1 [(a)] and HEMT 2 [(b)] for QB0. Symbols and solid lines are corresponding to measured and fitted data, respectively.

Table 5.3 List of $K_{00,LOW}$, $\theta_{0,LOW}$, and the ratio of $\left( \theta_{0,LOW} / K_{00,LOW} \right) R_{S0} I_{D0}^2$ to $V_{DS,LOW} \left( V_{GT0} - 1/2 V_{DS,LOW} \right)$ at $V_{GS} = 0 \, V$ of HEMT 1 and HEMT 2. $R_{S0} = R_{D0}$

<table>
<thead>
<tr>
<th>$R_{S0}$ (Ω)</th>
<th>$K_{00,LOW}$ (A/V²)</th>
<th>$\theta_{0,LOW}$ (V⁻¹)</th>
<th>$\frac{\left( \theta_{0,LOW} / K_{00,LOW} \right) R_{S0} I_{D0}^2}{V_{DS,LOW} \left( V_{GT0} - 1/2 V_{DS,LOW} \right)}$ at $V_{GS} = 0 , V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEMT</td>
<td>1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>10.5</td>
<td>~0.111</td>
<td>-</td>
<td>0.0667</td>
</tr>
<tr>
<td>10.0</td>
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<td>~0.139</td>
<td>0.180</td>
</tr>
<tr>
<td>9.5</td>
<td>~0.114</td>
<td>~0.141</td>
<td>0.296</td>
</tr>
<tr>
<td>9.0</td>
<td>-</td>
<td>~0.143</td>
<td>-</td>
</tr>
</tbody>
</table>

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Alternatively, $R_{S0}$ and $R_{D0}$ for QB0 extracted from the above procedure with different geometry HEMTs can be utilized to calculate $R_{Si}$ and $R_{Di}$ for the other QBs, while $R_{Si}$ and $R_{Di}$ for each QB can be extracted through the same procedure if surface trap activity of AlGaN/GaN wafers is uniform. However, uniform surface trap distribution in AlGaN/GaN HEMTs are not guaranteed in current AlGaN/GaN wafers and device processing can cause more trap sites or modify trap states. The following method to determine $R_{Si}$ and $R_{Di}$ for the other QBs using $R_{S0}$ and $R_{D0}$ for QB0 can be better to avoid any possible non-uniform trap activity at different QBs. This is because non-uniformly distributed surface traps in space and energy level do not respond to QB0 while they capture some electrons under the other conditions. Among the parasitic series resistance values for QB0 used in Figure 5.8, $9.5 \, \Omega$ for HEMT1 and $9.0 \, \Omega$ for HEMT2 are chosen as for $R_{S0}$ and $R_{D0}$ to extract $R_{Si}$ and $R_{Di}$ for other QBs. Here, QB1 and QB3 are intentionally chosen to analyze pulsed $I-V$ with QB2. Considering a negligible drain leakage current under these QBs, the source-to-gate bias under QB2 is the same as the source-to- and drain-to-gate biases under QB1 while the drain-to-gate bias under QB2 is almost equivalent to the source-to- and drain-to-gate biases under QB3. Again, a non-trapped source-to-/drain-to-gate region is presumably considered to have a constant resistance (i.e., $R_{Si}$ or $R_{Di}$) in our analysis while the trapped regions near both gate edges cause a gate-voltage dependent resistance and is incorporated into $L_{Gi,\text{eff}}$. Then, we can
apply Shift and Ratio (SR) method in Si MOSFETs [125] to the measured pulsed $I−V$ data of HEMT1 and 2 for $L_{Gi,\text{eff}}$ extraction. For example, if it is assumed that $\mu$ and $\theta$ values are the same for all QBs, the ratio of $\partial R_{mi}/\partial V_{GS}$ to $\partial R_{m0}/\partial V_{GS}$ at the same $V_{GTi}$ gives us $L_{Gi,\text{eff}}/L_{G0,\text{eff}}$ where $R_{mi}$ is the total resistance ($V_{DS}/I_{DS}$) for each QB. For the use of SR method, one caution is that the parasitic resistances at both source and drain sides (i.e., $R_{Si}$ and $R_{Di}$) have to be equal and constant. Otherwise, it would be too complicated to analyze $I−V$ characteristics using SR method with the derivative of $R_{mi}$ with $V_{GS}$. Under QB1 and QB3, it is expected that trapped regions at both gate edges are symmetrically formed, so $R_{Si}$ is equal to $R_{Di}$. However, since QB2 creates asymmetric trapped regions, the analysis based on SR method will be very complex. Instead, we can use $R_{S1}$ and $R_{D3}$ for $R_{S2}$ and $R_{D2}$, respectively. This is, as explained above, because the trapped region over the ungated AlGaN surface near the source-side gate edge for QB2 is equivalent to that for QB1 while the drain-side trapped region for QB2 is corresponding to that for QB3 in terms of $V_{GD}$. Note that surface trapping effects near the gate in the AlGaN/GaN HEMTs depend on gate-to-channel electrical field or potential difference under nearly zero-drain current QB conditions.

The procedure for extraction of device parameters for different QBs using QB0 data as follows: 1) the ratio of derivatives of total measured resistances (i.e., $\partial R_{mi}/\partial V_{GSi}/[\partial R_{m0}/\partial V_{GSo}]$) at the same $V_{GT}$ is determined for different QB1 and QB3 based
on SR method; 2) $R_{Si}$ and $R_{Di}$ for QB1 and QB3 are extracted using the assumed $R_{SO}$ and $R_{DO}$; 3) a gain factor ($K_{0,LOW}$) and $\theta_{i,LOW}$ is extracted from a plot of $K_i$ as a function of $V_{GTi}$, the modified SJ method, or fitted parameters to Eq. (5–10); 4) $L_{Gi,eff}$ is estimated by using the extracted either $K_{00,LOW}/K_{0,LOW}$ or $\alpha_i$ with $\theta_{i,LOW}$ and $\theta_{0,LOW}$.

Step 1) $\partial R_m/\partial V_{GSi}/[\partial R_{m0}/\partial V_{GS0}]$ for different QB1 and QB3: In applying SR method, we can directly deal with the measured data with the following equation of $R_{mi}$ derivative assuming all $\mu_{i,LOW}$ values are equal to $\mu_{0,LOW}$ [See Appendix A.3].

$$\frac{\partial R_{mi}}{\partial V_{GS}} = -\frac{L_{Gi,eff}}{\mu_{i,LOW} C_{IGaN} W_{G}} \left( V_{GTi} - \frac{1}{2} V_{DS,LOW} + 1 \right)^2$$

(5–13)

After the measured $R_{m0}$ values is shifted by the difference between $V_{Ti}$ and $V_{T0}$ ($\delta_i = V_{Ti} - V_{T0}$), division of the derivative of $R_{mi}$ by that of the shifted $R_{m0}$ at the same $V_{GT}$ (i.e., $\partial R_{mi}/\partial V_{GSi}/[\partial R_{m0}/\partial V_{GS0}]$) is equal to a constant $\alpha_i = L_{Gi,eff}(1/2\theta_{i,LOW} V_{DS,LOW} + 1)/[L_{G0,eff}(1/2\theta_{0,LOW} V_{DS,LOW} + 1)]$. As explained in Appendix A.3, an easier way is to utilize the fitted parameters in Eq. (5–10) to extract the fraction of $\partial R_{mi}/\partial V_{GSi}/[\partial R_{m0}/\partial V_{GS0}]$ at the same $V_{GTi}$ as in the following equation:

$$\frac{\partial R_{mi}(V_{GTi})}{\partial V_{GSi}} / \frac{\partial R_{m0}(V_{GT0}^0 - \delta_i)}{\partial V_{GS0}} = \frac{c_0^2 (b_i - a_i c_i)}{c_i^2 (b_0 - a_0 c_0)} = \alpha_i$$

(5–14)
where $\delta_i = (b_0/c_0 - b_i/c_i)$ is the difference in $V_T$ for QBi and QB0. When the fitting parameters in Table 5.2 are plugged into Eq. (5–14), the ratio $\alpha_i$ values are calculated as in Table 5.4. If $\theta$ values are known, $L_{G_{i,\text{eff}}}/L_{G_{0,\text{eff}}}$ values in both HEMTs can be calculated from the $\alpha_i$ values. For QB1, the $\alpha_i$ value for HEMT 1 is larger than that for HEMT 2, indicating that $L_{G_{1,\text{eff}}}$ value for HEMT 1 is longer than that for HEMT 2 with the same $L_{G_{0,\text{eff}}}$ for both HEMTs, even though current dispersion and $\Delta V_T$ are smaller in HEMT 1 than in HEMT 2 as shown in Table 5.4. Thus, comprehensive evaluation of trapping effects requires analysis of both $V_T$ shift and effective gate lengths.

Table 5.4 List of $\alpha_i$, normalized $\Delta V_T \times 100 = (V_{T0} - V_{Ti})/V_{T0}$ and $\Delta I_D \times 100 = (I_{D0} - I_{Di})/I_{D0}$, $2(R_{Di} - \alpha_i R_{D0})$, and $R_{Di} (= R_S)$ for QB1 and QB2 based on SR method. $R_{S0} (= R_{D0})$ values are 9.5 $\Omega$ and 9.0 $\Omega$ for HEMT 1 and HEMT 2, respectively.

<table>
<thead>
<tr>
<th>HEMT #</th>
<th>$\alpha_i$</th>
<th>Norm. $\Delta V_T \times 100$ (%)</th>
<th>Norm. $\Delta I_D \times 100$ (%)</th>
<th>$2(R_{Di} - \alpha_i R_{D0})$</th>
<th>$R_{Di}$ (Ω)</th>
</tr>
</thead>
<tbody>
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<td>HETM 1</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>~8.5</td>
<td>~5.6</td>
<td>~23.6</td>
<td>~40.0</td>
</tr>
</tbody>
</table>

Step 2) Extraction of $R_{Si}$ and $R_{Di}$ for QB1 and QB3: $R_{Di} (= R_S)$ for QB1 and QB3 can be extracted using the same procedure for $R_{D0}$ for QB0 as described above. Not to mention uniform trap activity at each QB, it requires at least two HEMTs with different gate
lengths and the same spacing between source/drain contacts and gate. Instead, the relationship (Eq. 5–15) between \( R_{S0} \) and \( R_{Si} \) derived in Appendix A.4 is used to calculate \( R_{Si} \) and \( R_{Di} \) with the assumed \( R_{D0} \) at the same \( V_{GT} \).

\[
2(R_{Di} - \alpha_i R_{D0}) = \frac{V_{DS,LOW} (c_0 - \alpha_i c_i)}{c_0 c_i} \quad (5-15)
\]

Table 5.4 lists the calculated \( R_{Di} \) values of HEMT1 (\( R_{D0} = 9.5 \, \Omega \)) and HEMT2 (\( R_{D0} = 9.0 \, \Omega \)) for QB1 and QB3. \( R_{Di} \) values are smaller than \( R_{D0} \), indicating that the gate-voltage dependent area is extended toward source and drain contacts, so the constant resistance regions become shorter than QB0 case. Namely, the trapped region over the ungated AlGaN surface is spread toward ohmic contacts under QB1 or QB3. Again, \( R_{Si} \) or \( R_{Di} \) are resistances for the non-trapped access region, and \( V_{Ti}, L_{Gi,eff} \) and \( \theta_i \) include effects of the extended trapped access region.

3) Step 3. Calculation of \( K_{0i}' \) and \( \theta_i \) for all QBs: Once \( R_{Si} \) and \( R_{Di} \) are extracted, there are three ways to extract \( K_{0i}' \) and \( \theta_i \) for QB1 and QB3. First, \( K_{0i}' \) and \( \theta_i \) can be obtained by fitting the following equation of the modified SJ method [Eq. (5–12)] to the measured \( I_D-V_{GS} \) data as shown in Figure 5.7.

\[
R_{mL} \left( V_{GTi} - 1/2V_{DS,LOW} \right) = \left( \frac{\theta_{i,LOW}}{K_{0i,LOW}} + R_{Ti} \right) V_{GTi} + \frac{1}{K_{0i,LOW}} V_{DS,LOW} R_{Di} \quad (5-12)
\]
Based on the fitting results of Figure 5.7, $K_{0,\text{LOW}}$ can be calculated from y-intercept in a plot of $R_m(V_{GTi} - 1/2 V_{DS})$ versus $V_{GTi}$ with $R_{Di}$ determined in the previous step. Then, $\theta_i$ is determined from the slope of the plot by plugging $K_{0i}'$ and $R_{Ti}$ (=2 $R_{Di}$). Second, the relationship between non-linear fitting parameters of Eq. (5−10), and both slope and y−intercept in Eq. (5−12) are used to calculate $K_{0i,\text{LOW}}$ and $\theta_{i,\text{LOW}}$ for all QBs. The last way is to use a plot of $K_i$ as a function of $V_{GTi}$ based on Eq. (5−10). Then, $K_{0i,\text{LOW}}$ and $\theta_{i,\text{LOW}}$ can be extracted by fitting $K_i = K_{0i}'[1+\theta_i(V_{GTi}−I_{Di}R_{Si})]$ to the measured data of $K_i$ and $(V_{GTi}−I_{Di}R_{Si})$ as shown in Figure 5.9. Note that the extracted $R_{S1}$ and $R_{D3}$ are used as $R_{S2}$ and $R_{D2}$, respectively, for QB2, and $I_{Di}R_{Si}$ effect on $K_{0i,\text{LOW}}$ and $\theta_{i,\text{LOW}}$ is negligible for $V_{GT} > 1$ V. Table 5.5 lists the slopes, y−intercepts, and calculated $K_{0i,\text{LOW}}$ and $\theta_{i,\text{LOW}}$ using these three methods. Clearly, all three methods give us essentially the same extracted values.

4) Step 4. $L_{Gi,\text{eff}}$ calculation for all QBs: Effective gate length ($L_{Gi,\text{eff}}$) can be estimated with the extracted $K_{0i,\text{LOW}}$ (Table 5.5) values by assuming that low-drain-bias mobility ($\mu_{i,\text{LOW}}$) is a specific value (i.e., 800 cm/Vs) for all HEMTs. Table 5.6 lists all the extracted $L_{Gi,\text{eff}}$ for different QBs assuming $\mu_{0,\text{LOW}} = 800$ cm/Vs, and $R_{S0}$ (= $R_{D0}$) values are 9.5 $\Omega$ and 9.0 $\Omega$ for HEMT 1 and HEMT 2, respectively, with $C_{\text{AlGaN}} = \sim 3.6 \times 10^{-7}$ F/cm$^2$ and the physical gate length ($L_G$) = \sim 0.2 \mu m. The calculated $K_{00,\text{LOW}}$
values are in the range of 0.111–0.144 A/V$^2$, and the calculated $L_{G0,eff}$ values for QB0 are in the range of 0.25–0.26 μm for HEMT 1 and 0.19–0.20 μm for HEMT 2. $L_{Gi,eff}$ for all QBs can be calculated by taking ratios of $K_{00,LOW}$ to $K_{0i,LOW}$ and multiplying the ratios by the calculated $L_{G0,eff}$. As shown in Table 5.6, a more negative biases for quiescent bias point causes a longer effective gate length. One can notice that $L_{G3,eff}$ of HEMT 2 showing a larger current dispersion is much longer than that of HEMT1 with less current dispersion while $L_{G1,eff}$ of HEMT 2 is a little shorter than that of HEMT1. Thus, the trapping effects are reflected in all the device parameters such as $V_{Ti}$, $L_{Gi,eff}$, $R_{Si}$ ($R_{Di}$), and $\theta_{i,LOW}$ possibly with $n$ factor in the field dependent mobility.

![Figure 5.9](image-url)
Table 5.5 List of the slope and y-intercept in the modified SJ plot from direct SJ method and non-linear fitting method, and extracted $K_{0,LOW}$ and $\theta_{i,LOW}$ from three different methods: (a) Modified SJ method, (b) non-linear curve fitting, (c) fitting with $K_i = K_{0,LOW}/[1+ \theta_{i,LOW}(V_{GTi}-I_{DiRSi})]$.

<table>
<thead>
<tr>
<th>HEMT#</th>
<th>Slope (Ω)</th>
<th>y-intercept (VΩ)</th>
<th>$K_{0,LOW}$ (A/V²)</th>
<th>$\theta_{i,LOW}$ (V⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>2</td>
</tr>
<tr>
<td>QB0</td>
<td>~21.5⁺a</td>
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<tr>
<td></td>
<td>~20.5⁺a</td>
<td>~6.88⁺b</td>
<td>~4.67⁺a</td>
<td>~0.114⁺b</td>
</tr>
<tr>
<td></td>
<td>~20.3⁺b</td>
<td>~5.23⁺b</td>
<td>~0.111⁺c</td>
<td>~0.111⁺c</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~0.155⁺a</td>
<td>~0.142⁺b</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~0.144⁺c</td>
<td>~0.144⁺c</td>
</tr>
<tr>
<td>QB1</td>
<td>~22.1⁺a</td>
<td>~22.3⁺b</td>
<td>~10.1⁺a</td>
<td>~0.0561⁺a</td>
</tr>
<tr>
<td></td>
<td>~22.3⁺b</td>
<td>~15.5⁺b</td>
<td>~0.0580⁺b</td>
<td>~0.0840⁺a</td>
</tr>
<tr>
<td></td>
<td>~22.0⁺b</td>
<td>~10.5⁺b</td>
<td>~0.0579⁺c</td>
<td>~0.0811⁺b</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~0.0794⁺c</td>
<td>~0.0794⁺c</td>
</tr>
<tr>
<td>QB2</td>
<td>~22.4⁺a</td>
<td>~25.7⁺b</td>
<td>~34.5⁺a</td>
<td>~0.0477⁺a</td>
</tr>
<tr>
<td></td>
<td>~22.3⁺b</td>
<td>~19.3⁺b</td>
<td>~0.0478⁺c</td>
<td>~0.0285⁺a</td>
</tr>
<tr>
<td></td>
<td>~25.7⁺b</td>
<td>~19.3⁺b</td>
<td>~0.0477⁺c</td>
<td>~0.0285⁺a</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~0.0285⁺c</td>
<td>~0.0285⁺c</td>
</tr>
<tr>
<td>QB3</td>
<td>~23.9⁺a</td>
<td>~24.8⁺b</td>
<td>~59.9⁺b</td>
<td>~0.0360⁺a</td>
</tr>
<tr>
<td></td>
<td>~24.3⁺b</td>
<td>24.5⁺b</td>
<td>~0.0382⁺b</td>
<td>~0.0165⁺a</td>
</tr>
<tr>
<td></td>
<td>~25.2⁺b</td>
<td>~58.2⁺b</td>
<td>~0.0366⁺c</td>
<td>~0.0162⁺c</td>
</tr>
</tbody>
</table>

Table 5.6 List of effective gate lengths ($L_{Gieff}$) of HEMT 1 and HEMT 2 using three different methods: MSJ = Modified SJ method, NLF = Non-linear curve fitting, KF = . Fitting with $K_i = K_{0,LOW}/[1+ \theta_{i,LOW}(V_{GTi}-I_{DiRSi})]$, $a$ = SR ratio with Eq. (A4–5)

<table>
<thead>
<tr>
<th>Method</th>
<th>$L_{Gieff}$ of HEMT1 (µm)</th>
<th>$L_{Gieff}$ of HEMT2 (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>MSJ</td>
<td>NLF</td>
</tr>
<tr>
<td>QB0</td>
<td>~0.26</td>
<td>~0.25</td>
</tr>
<tr>
<td>QB1</td>
<td>~0.51 (−0.51)⁺a</td>
<td>~0.50 (−0.50)⁺a</td>
</tr>
<tr>
<td>QB2</td>
<td>~0.60</td>
<td>~0.60</td>
</tr>
<tr>
<td>QB3</td>
<td>0.8 (0.77)⁺a</td>
<td>~0.75 (−0.75)⁺a</td>
</tr>
</tbody>
</table>
Up to now, the condition of Eq. (5–11) is assumed to be valid to extract all the device parameters. It should be verified by plugging the extracted $K_{0_{\text{LOW}}}, \theta_{\text{LOW}}, R_{Si},$ and $R_{Di}$ back into Eq. (5–11). Using the device parameters by non-linear curve fitting, ratios of the left-side to the right-side in Eq. (5–11) 
\[
\frac{\theta_{\text{I}}}{K_{0_{\text{I}}}R_{Si}+1/2(R_{Si}2-R_{Di}^2)}I_{Di}^2/
[(V_{GTI}-1/2V_{DS})V_{DS}]
\]
are $2.0\times10^{-3}$ to $5.8\times10^{-3}$ ($1.8\times10^{-3}$ to $7.4\times10^{-3}$), $3.0\times10^{-3}$ to $6.3\times10^{-3}$ ($2.4\times10^{-3}$ to $7.0\times10^{-3}$), $2.4\times10^{-3}$ to $5.1\times10^{-3}$ ($3.2\times10^{-3}$ to $4.9\times10^{-3}$), and $1.9\times10^{-3}$ to $5.6\times10^{-3}$ ($8.0\times10^{-4}$ to $2.2\times10^{-3}$) for QB0, QB1, QB2, and QB3, respectively, in HEMT1 (HEMT2) over the $V_{GS}$ range for all the analysis. This indicates that all deviation in applying the extracted parameters to Eq. (5-10) is within less than 1 % deviation between the measured and modeled $I_D-V_{GS}$ at $V_{DS,\text{LOW}}$. Since $V_{Ti}$ values for different QBs are shifted by more than 1.1 % ~ 8.5 % than $V_{Ti0}$ for QB0 as in Table 5.4, all the extracted $\Delta V_{Ti}$ values are considered to be meaningful in interpreting different trapping effects with various QBs.

5.4 Modeling of pulsed $I_D-V_{DS}$ characteristics in the linear region

This section describes modeling of 0.2 $\mu$s pulsed $I_D-V_{DS}$ characteristics in the linear region with consideration of trapping effects. Based on Model 2, $V_{Ti}$ values were
extracted and the other parameters were determined using the assumed \( R_{S0} \) and \( R_{D0} \) values in 0.2 \( \mu s \) pulsed \( I_D-V_{GS} \) characteristics at \( V_{DS,LOW} \). In this section, HEMT modeling is first performed within the low drain voltage range (< 1V) in the linear region of 0.2 \( \mu s \) pulsed \( I_D-V_{DS} \) characteristics. Then, the modeling in the entire triode region is performed.

5.4.1 Low-voltage range in the linear region of 0.2 \( \mu s \) pulsed \( I_D-V_{DS} \) characteristics

The model equation for the linear region of \( I_D-V_D \) characteristics can be written as:

\[
I_D = \frac{C_{AlGaN} \mu_{0,LOW} W_G / L_{Gi,eff}}{\left[1 + \beta_{i,LOW} \left(V_{GTi} - I_{Di} R_{Si}\right)\right]^{\frac{1}{\eta_i}} + \left[\eta_i \left(V_{DS} - I_{Di} R_{Ti} \right)^{\eta_i} \right]}^{\frac{1}{\eta_i}} \times \left[V_{GTi} - 1/2 \left(V_{DS} - I_{Di} (R_{Di} - R_{Si})\right) \right]^{\frac{1}{\eta_i}} \quad (5-16)
\]

where \( \eta_i = 1/[L_{Gi,eff} E_C] \), \( E_C \) is a critical field \((=v_{sat}/ \mu_{high,eff})\), \( v_{sat} \) is saturation velocity \((2 \times 10^7 \text{ cm/s})\), and \( \mu_{high} \) is constant mobility at a high vertical field \((V_{GS} = 0 \text{ V})\). The mobility expression in our model takes the empirical form as in Eq. (5–9). However, while \( E_C \) \((=v_{sat}/ \mu_{high,eff})\) is a function of vertical field due to the effective mobility \((\mu_{high,eff})\) in Si MOSFETs, constant high-field mobility is used in our model since field-dependent mobility model in 0.2 \( \mu s \) pulsed \( I-V \) measurements of AlGaN/GaN HEMTs are different from that in Si MOSFETs due to a minimal thermal effects and high optical
phonon energy in GaN (~92meV) [27, 92]. If $E_C = \nu_{sat} / \mu_{eff}$ is utilized, the modeled $I_D-V_{GS}$ characteristics do not match with the measured ones at all $V_{GS}$s at the same time as shown in Figure 5.10 and Figure 5.11.

Figure 5.10 Measured and modeled 0.2 μs pulsed $I_D-V_{DS}$ characteristics of HEMT 1 at QB0: (a) when the modeled data is fit to $I_D-V_{DS}$ at $V_{GS} = 0$ V by adjusting $R_{Si}, R_{Di}$, and $n$ values. (b) $n = 1.5$ & $R_s=R_D=2\Omega$ (c) $n = 2$ & $R_s=R_D=1\Omega$.
Figure 5.11 Measured and modeled 0.2 μs pulsed $I_D-V_{DS}$ characteristics of HEMT 1 at QB0 when the modeled data are fit to $I_D-V_{DS}$ at $V_{GS} = -3$ V by adjusting $R_{Si}$, $R_{Di}$, and $n$ values.

Since the analyzed HEMTs have the same gate length, $R_{Si}$, and $R_{Di}$ values cannot be extracted using Model 2 as described above. Instead, $R_{Si}$ and $R_{Di}$ values are adjusted to
get the best fit to the measured data in which case the other parameters such as $K_{0i,LOW}$ and $\theta_{i,LOW}$ are calculated using each set of $R_{Si}$ and $R_{Di}$ from the relationship between non-linear curve fitting parameters and device parameters (i.e., $V_{DS,LOW}/c_i = \theta_{i,LOW}/K_{0i,LOW} + R_{Ti}$ and $(a_i + V_{Ti}) = (c_i/V_{DS,LOW})/K_{0i,LOW} - c_iR_{Di}$) as described in Section 5.3.2. Depending $R_{Si}$ and $R_{Di}$ values $n$ values are also adjusted for the best fit to the measured $I_D-V_{GS}$ characteristics. As in Figure 5.10 and 5.11, when the modeled data are fit to $I_D-V_{DS}$ at $V_{GS} = 0 \, \text{V}$, the modeled curve at $V_{GS} = -3 \, \text{V}$ doesn’t match with the measured one and vice-versa. However, when constant $E_C = 126 \, \text{kV/cm}$ ($\mu_{\text{high}} = \sim 79.3 \, \text{cm}^2/\text{Vs}$), $v_{\text{sat}} = 1\times 10^7 \, \text{cm/s}$, and $n = 1$ are is used, the modeled $I_D-V_{DS}$ characteristics fit very well to the measured ones when both $R_{S0}$ and $R_{D0}$ are $6.8 \, \Omega$, and $R_{S2}$ and $R_{D2}$ are $3 \, \Omega$ and $2 \, \Omega$, respectively, as shown in Figure 5.12. Table 5.7 lists device parameters used for modeling of 0.2 $\mu$s pulsed $I_D-V_{DS}$ characteristics in the linear region ($V_{DS} < 1 \, \text{V}$). Assuming $L_{G0,\text{eff}}$ for QB0 (trapping free) is the physical gate length 0.2 $\mu$m , $L_{G2,\text{eff}}$ (QB2) = $K_{0,LOW}$ (QB0)/ $K_{02,LOW}$ (QB2) and the calculated $\mu_{0,LOW}$ [ = $K_{0,LOW} L_{G0,\text{eff}} / (C_{AlGaN} W_{G})$] is 674.3 $\text{cm}^2/\text{Vs}$, equal to $\mu_{2,LOW}$ for QB2. Again, note that $R_{S2}$ and $R_{D2}$ for QB2 case are expected to be lower values than those for QB0 case because $R_{ST}$ and $R_{DT}$ for QB2 are incorporated into the effective gate length and gate-modulated effective channel resistance. In addition, $R_{S2}$

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will be larger than $R_{D2}$ since the drain-side trapped region is more extended than the source-side one, resulting in decrease in length of constant parasitic resistance region.

Figure 5.12 Measured and modeled 0.2 μs pulsed $I_D-V_{DS}$ characteristics of HEMT 1 at QB0 [(a)] and QB2 [(b)] by adjusting $R_{Si}$ and $R_{Di}$ values with n =1 where $R_{S0} = R_{D0} = 6.8 \Omega$, and $R_{S2} = 3 \Omega$ and $R_{D2} = 2 \Omega$.

Table 5.7 List of the extracted device parameters assuming n=1. $R_{Si}$ and $R_{Di}$ values for both QBs are the values for the best fit. The other parameters are calculated using the $R_{Si}$ and $R_{Di}$ values. $\mu_{0,LOW} = \mu_{2,LOW} = 674.3$ cm$^2$/V·s.

<table>
<thead>
<tr>
<th></th>
<th>$R_{Si}$ (Ω)</th>
<th>$R_{Di}$ (Ω)</th>
<th>$K_{0i,LOW}$ (A/√V)</th>
<th>$\theta_{i,LOW}$ (V·1)</th>
<th>$L_{Gi,eff}$ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QB0</td>
<td>6.8</td>
<td>6.8</td>
<td>~0.121</td>
<td>~0.971</td>
<td>0.2</td>
</tr>
<tr>
<td>QB2</td>
<td>3</td>
<td>2</td>
<td>~0.0509</td>
<td>~0.882</td>
<td>~0.48</td>
</tr>
</tbody>
</table>
5.4.2 Entire linear region of 0.2 μs pulsed $I_D-V_{DS}$ characteristics

To perform the entire linear region of 0.2 μs pulsed $I_D-V_{DS}$ characteristics, we start with Eq. (5–16). $n = 1$ is used for simplicity. Figure 5.13 shows the measured and modeled 0.2 μs pulsed $I_D-V_{DS}$ characteristics using device parameters extracted in the low drain voltage range. As one can see, the measured and fitted data are in good agreement within a lower $V_{DS}$ range as in Figure 5.13, but start to deviate from each other at a certain $V_{DS}$ before the saturation.

![Figure 5.13 Measured and modeled 0.2 μs pulsed $I_D-V_{DS}$ characteristics of HEMT 4 at QB0 without a correction factor in the linear region. Note that $R_{SD} = R_{D0} = 4 \, \Omega$ and $n = 1$ for QB0. $E_C = 140 \, \text{kV/cm}$, $\mu_{0,LOW} = -497.5 \, \text{cm}^2/\text{Vs}$, and $v_{sat} = 1 \times 10^7 \, \text{cm/s}$.](image)

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Figure 5.14 Drift velocity ($v_{drift}$) with respect to lateral electric field with two different expressions of drift velocity in the linear region. Note that $R_s = R_D = 4 \, \Omega$ and $n = 1$ for QB0, and measured $I_D$ is used for $v_{drift}$ calculation. $v_{drift}$ with Eq. (5−17) is essentially measured one using extracted device parameters (i.e., $V_{Ti}$, $R_S$, and $R_D$), and $v_{drift}$ with Eq. (5−18) for (a) and Eq. (5−19) for (b) is modeled one based on our proposed model.

Figure 5.14 (a) shows the measured and modeled electron drift velocity ($v_{drift}$) of HEMT 4 for QB0 with respect to lateral field based on Eq. (5−17) and Eq. (5−18), respectively, as follows:

$$v_{Drift,1}(E_{Lateral}) = \frac{I_{Di}}{C_{AlGaAs}W_G(V_{GTi} - 1/2 |V_{DS} - I_{Di}(R_{Di} - R_{Si})|)}$$  \hspace{1cm} (5−17)$$

$$v_{Drift,2}(E_{Lateral}) = \frac{\mu_{0,LOW}}{[1 + \theta_{i,LOW}(V_{GTi} - I_{Di}R_{Si})] \left[1 + \left(\frac{V_{GTi} - I_{Di}R_{Ti}}{L_{Gi,eff}E_C}\right)^n\right]} \times \frac{V_{DS} - I_{Di}R_{Ti}}{L_{Gi,eff}}.$$  \hspace{1cm} (5−18)$$

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Since $R_{S0}$ is equal to $R_{D0}$ for QB0, no extracted parameters except for $V_{Ti}$ are necessary to use for the measured $v_{drift}$ as in (Eq. 5–17), so the accuracy of the measured $v_{drift}$ depends on that of $V_{Ti}$ value. The modeled $v_{drift}$ is calculated with the device parameters extracted in low-voltage range of 0.2 $\mu s$ pulsed $I_D-V_{DS}$ characteristics (Eq. 5–18). Figure 5.14 (a) shows that the deviation starts at $v_{drift} = 3$–$5 \times 10^6$ at different $V_{GS}$ values where drain current is not saturated yet, and a lower $V_{GS}$ leads to a lower critical field ($E_{C,eff}$), defined as the lateral field at $v_{drift} = 8.3 \times 10^6$ cm/s at different $V_{GS}$ values in this particular case (not well-defined yet) as expected in Si-MOSFETs. To minimize the deviation, a correction factor is included to the modeled $v_{drift}$ expression as in Eq. (5–19).

$$v_{Drift,2} (E_{Lateral}) = \frac{f \left( \frac{E_{Lateral}}{E_{C,eff}} \right)}{\mu_{0,LOW}} \times \frac{V_{DS} - I_{Di} R_{Gi}}{L_{G_i,eff}} \left[ 1 + \theta_i,LOW \left( V_{GTi} - I_{Di} R_{Si} \right) \left[ 1 + \left( \frac{V_{GTi} - I_{Di} R_{Si}}{L_{G_i,eff} E_C} \right)^n \right] \right] \times \left[ 1 + \left( \frac{E_{Lateral}}{E_{C,eff}} \right) \right]^{1/m} \mu_{0,LOW} \times \frac{V_{DS} - I_{Di} R_{Gi}}{L_{G_i,eff}}$$

(5–19)

In this way, the correction factor is treated as a function of $E_{Lateral}/E_{C,eff}$, so the gate voltage effects on this factor can be minimized and are independent of $V_{GS}$. By
including the correction factor, the measured and fitted data are well-matched in the entire linear region of $I_D-V_{DS}$ characteristics before saturation as shown in Figure 5.14 (b). Figure 5.15 shows that the modeled and measured $I_D-V_{DS}$ characteristics have also very good agreements for both QB0 and QB2 with a correction factor. Compared with QB0 condition, at QB2 bias, the $V_T$ shifts by 0.14 V and $L_{G2,eff}$ increases to 0.28 μm when $L_{G0,eff}$ is assumed to 0.2 μm. The effective trap density is $3.15 \times 10^{11}$/cm$^2$. Again, the definition of $E_{C,eff}$ is not optimized yet, meaning that different $E_{C,eff}$ values for the same HEMT can lead to different $l$ and $m$ values. In Figure 5.16, $E_{C,eff}$ values are defined as lateral fields at $\sim 8.50 \times 10^6$ cm/s for QB0 and $\sim 4.42 \times 10^6$ cm/s for QB2 at each $V_{GS}$. The correction factor is expressed as:

$$f \left( \frac{E_{Lateral}}{E_{C,eff}} \right) = \left[ 1 + \left( \frac{E_{Lateral}}{aE_{C,eff}} \right)^{l/m} \right]$$  \hspace{1cm} (5 – 20)

In addition, $l$ and $m$ values are set to be equal. Adjustment of $l$ and $a$ values is performed to fit the calculated drift velocity to $v_{Drift}$ in Eq. (5–18) and to be $v_{SAT} = \sim 1 \times 10^7$ cm/s for QB0 and $v_{SAT} = \sim 5.20 \times 10^6$ cm/s for QB2. Figure 5.16 shows that the well-fitted pulsed $I-V$s for both QB0 and QB2 can be obtained with a correction factor of Eq. (5–18). Table 5.8 lists all the device parameters and average deviation where $l = m = 2$ and $a = 2.3$ for QB0, and $l = m = 2.5$ and $a = 3.5$ for QB2. While our proposed model is applicable to
analyze the linear region in the presence of trapping effects, further modeling in both the linear and saturation regions is required to determine more accurate parameters.

Figure 5.15 Measured and modeled 0.2 μs pulsed $I_D-V_{DS}$ characteristics of HEMT 4 with a correction factor for QB0 = ($V_{DSQ}$, $V_{GSQ}$) = (0 V, 0V) and QB2 = ($V_{DSQ}$, $V_{GSQ}$) = (7V, −5V) Note that $R_{SO}=R_{D0} = 4 \, \Omega$, $n = 1$, $l = 2.5$, and $m = 8$ for QB0, and $R_{SO} = 4 \, \Omega$, $R_{D2} = 3.5 \, \Omega$, $n = 1$, $l = 4$, $m = 8$ for QB2.
Figure 5.16 Measured and modeled 0.2 μs pulsed $I_D-V_{DS}$ characteristics and drift velocities of HEMT 4: (a) and (b) are for QBO = ($V_{DSQ}$, $V_{GSQ}$) = (0 V, 0 V) with $R_{S0} = R_{D0} = 4 \Omega$, $n = 1$, $l = m = 2$ and $a = 2.3$ for QBO, and (c) and (d) QB2 = ($V_{DSQ}$, $V_{GSQ}$) = (7 V, -5 V) with $R_{S2} = 3.8 \Omega$, $R_{D2} = 3 \Omega$, $n = 1$, $l = m = 2.5$ and $a = 3.5$ for QB2. Note that $E_C$ is 140 kV/cm for QBO and QB2.

Table 5.8 List of all the device parameters for the fitted $I_D-V_{DS}$ at different $V_{GS}$ values

<table>
<thead>
<tr>
<th></th>
<th>$V_T$ (V)</th>
<th>$R_S/R_D$ (Ω)</th>
<th>$K_{th,eff}$ (A/V²)</th>
<th>$\mu_{i,LOW}$ (cm²/V·s)</th>
<th>$\theta_{i,LOW}$ (V⁻¹)</th>
<th>$L_{Gi,eff}$ (µm)</th>
<th>$E_C$ (kV/cm)</th>
<th>Ave. Dev</th>
<th>$n_{trap,eff}$ (#/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>QBO</td>
<td>-4.50</td>
<td>4/4</td>
<td>-0.0896</td>
<td>498</td>
<td>-0.859</td>
<td>0.2</td>
<td>140</td>
<td>~3.86%</td>
<td>-</td>
</tr>
<tr>
<td>QB2</td>
<td>-4.36</td>
<td>3.8/3</td>
<td>-0.0640</td>
<td>498</td>
<td>-1.20</td>
<td>-0.28</td>
<td>140</td>
<td>~2.42%</td>
<td>3.15×10¹¹</td>
</tr>
</tbody>
</table>
The drift velocity characteristics with lateral field at different $V_{GS}$ (Figure 5.14 and Figure 5.16 (b) & (d)) clearly show that the drift velocity is lower at a higher $V_{GS}$, indicating that interface roughness scattering effect is one of the dominant scattering mechanism [92]. In addition, the saturation current with respect to $V_{DS}$ at different $V_{GS}$ values exhibits different slopes shown in Figure 5.17. It may be because of thermal effects at a higher $V_{GS}$ (so, a higher current) as Ref. [96] considered the phonon effects in their simulation, even if a very short pulse width is used in this work. Note that the saturation currents (the blue straight line in Figure 5.17 are simply the ending drain current values in the linear region of the modeled $I$-$V$ characteristics. At this moment, it is not clear whether the constant saturation velocity model is good due to thermal effects at high current operation (i.e., high $V_{GS}$ and high $V_{DS}$). Again, further investigations including the saturation region are required.
Figure 5.17 Measured and modeled 0.2 μs pulsed $I_D-V_{DS}$ characteristics of HEMT 4: (a) for $QB0 = (V_{DSSQ}, V_{GSQ}) = (0 \text{ V}, 0\text{ V})$ and (b) $QB2 = (V_{DSSQ}, V_{GSQ})=(7\text{ V}, -5\text{ V})$. The blue straight line is the saturation current using $C_{AlGaN}W_{Gsat}(V_{GT-I_{D,sat}R_S})$ and $v_{sat}$ value are adjusted to match the end of the linear region (Not the optimized values). Note that the measured and modeled data in the linear regions are the same as in Figure 5.16 (a) and (c).

5.5 Discussion: impact on surface electron trapping on AlGaN/GaN HEMT operation

This section describes interpretation of device parameters extracted from pulsed $I-V$ characteristics with a very short pulse width and impact of electron trapping over the ungated AlGaN surface on AlGaN/GaN HEMT operation.
In this work, it is assumed that there is no electron trapping during HEMT operation for QB0 cases with 0.2 μs pulsed width. That is why 0.2 μs pulsed $I-V$ a at QB0 was used as a reference for trap characterization. 0.2 μs pulsed $I-V$ characteristics at QB1, QB2, and QB3 case exhibit drain current degradation compared with 0.2 μs pulsed $I-V$ a at QB0. This is because a high negative potential difference between gate and drain contacts leads to some electrons injected into the ungated AlGaN surface near the drain-side gate edge by tunneling [14, 35]. The injected electrons are trapped on the AlGaN surface. The trapped charges on the AlGaN deplete 2DEG in the channel as many researchers have mentioned. Owing to a very short pulse width, impact of the electron trapping fully reflects device performance during HEMT operation. In the previous sections, based on our proposed model, device parameters such as $V_{T_i,eff}$ ($n_{trap,eff}$), $L_{G_i,eff}$, $μ_{i,LOW}$, and $θ_{i,LOW}$ were extracted from 0.2 μs pulsed $I-V$ at different QBs by adjusting $R_{Si}$ and $R_{Di}$ values and assuming that n = 1 and $L_{G0,eff}$ for QB0 is 0.2 μm. As illustrated in the previous sections, a larger current dispersion generally causes higher $V_T$ shift in the positive direction, a longer effective gate length, and/or smaller access resistance. This is because a higher negative potential difference between gate and drain contacts causes injection and trapping of more electrons and extend the trapped region further toward the drain contact. Figure 5.18 graphically shows a hypothetic distribution of the trapped electrons on the AlGaN surface with a schematic conduction band diagram at AlGaN
surface and AlGaN/GaN interface at different bias conditions to illustrate gate-bias modulation of the ungated channel under the trapped AlGaN surface.

Figure 5.18 Schematic band diagrams of AlGaN/GaN HEMTs: (a) under QB2 = \((V_{DSQ}, V_{GSQ}) = (7\text{ V}, -6\text{ V})\), (b) within ~0.2 \(\mu\)s after the pulse signal changes from QB2 to \((V_{DS}, V_{GS}) = (0\text{ V}, 0\text{ V})\), and (c) within ~0.2 \(\mu\)s after the pulse signal changes from QB2 to \((V_{DS}, V_{GS}) = (2\text{ V}, -3\text{ V})\), and (d) within ~0.2 \(\mu\)s after the pulse changes from QB2 to \((V_{DS}, V_{GS}) = (7\text{ V}, 0\text{ V})\). Note that \(V_{\text{surface}}\) is the surface potential of electron-trapped and ungated AlGaN surface near the gate edge.
Under $QB2 = (V_{DSQ}, V_{GSQ}) = (7 \ \text{V}, -6 \ \text{V})$, some electrons are trapped within 2 ms (Figure 5.18(a)). The trapped region in the drain side is more extended toward the drain contact than in the source since the potential difference in the drain side is higher than in the source side. Figure 5.18 (b), (c), and (d) are corresponding to possible energy band diagrams with trapped electrons at different $(V_{DS}, V_{GS}) \sim 0.2 \ \mu\text{s}$ after the biases pulses from $QB2$ to these bias points. Distribution of the quasi-Fermi level over the trapped AlGaN surface (Figure 5.18(b)) is the same as surface potential distribution reported by Koley et al. (Figure 1.6) Those trapped electrons are frozen, so they are considered to act like fixed charges as in the lightly-doped region of LDD MOSFETs. Then, the conduction in the partially depleted channel below the trapped region is modulated by the gate bias while the gate-modulation in this region is considered to be weaker than the channel under the gate. It is considered in our model that, as shown in Figure 5.18(d), the channel pinch-off for drain current saturation occurs at the channel underneath the trapped ungated AlGaN surface as Koudymov et al mentioned [27]. Spatial distribution and density of the trapped electrons affect device parameters based on our proposed model. So far, we have focused on electron trapping on the surface since Koley et al. demonstrated surface potential change on the ungated AlGaN surface when the bias changes from the pinch-off to turn-on or zero bias [35]. Electron trapping in the GaN buffer is possible but it is hard to characterize the buffer trapping only by excluding the
surface trapping. The buffer trapping is coupled with electron trapping on the AlGaN surface to keep overall charge neutrality but the mechanism is unclear.

5.6 Summary

In summary, two models for quantitatively characterizing trapping effect in AlGaN/GaN HEMTs were presented based on 0.2 μs pulsed $I-V$ characteristics. It was demonstrated that the current collapse due to electron trapping can be analyzed in terms of various device parameters in AlGaN/GaN HEMTs. A higher negative electric field between gate and drain contacts cause a larger current dispersion due to trapping of more electrons, leading to a higher $V_T$ shift in the positive direction, a longer effective gate length, and smaller parasitic resistances. Electron drift velocity characteristics based on our model showed that drift velocity at a higher $V_{GS}$ is lower due to more interface roughness scattering and the thermal effect especially at high current operation region even in 0.2 μs pulsed $I-V$ characteristics. A mechanism of gate-bias modulation in the ungated channel below the trapped region was discussed. Finally, it is suggested that our methods can be applied for AlGaN/GaN HEMT modeling in presence of trapping effects for evaluation of newly-introduced device/growth techniques, monitoring of device
fabrication process, and, potentially, circuit applications while further systematic modeling including the saturation region is required.
Chapter 6: Summary and Future Work

6.1 Summary

Trapping effects in AlGaN/GaN HEMTs have been investigated to develop qualitative and quantitative characterization methods of trap activities.

First, impact of post-gate annealing (PGA) on trap activity in AlGaN/GaN HEMTs have been investigated based on DC and pulsed $I-V$ characterizations, temperature-dependent drain current transient measurements, and reverse-gate current characterizations. It was demonstrated that PGA modifies trap activities in AlGaN/GaN HEMTs, causing change in drain current dispersion between DC and pulsed $I-V$ characteristics. The PGA process removes shallow traps with an activation energy of $\sim 38$ meV and $t_E$ of $\sim 0.5 \, \mu s$ at 295 K and induces deeper traps at least with an activation energy of $\sim 0.31 \, eV$ and $t_E$ of $\sim 21.6 \, \mu s$ at 295 K. Shallow traps result in fast drain current transient and high reverse gate leakage current while deep traps lead to slow current recovery but a small leakage current. It was also shown that trap activities are dependent on measurement conditions for trap characterization.

Second, EBIC and XPS analyses have been performed to investigate electrical properties of interface states at Ni/AlGaN interface and unintentional reaction on the free
AlGaN surface due to PGA. The EBIC images showed that the post-annealing reduced the density of the electrically active states at the Schottky metal/AlGaN surface, leading to decrease of reverse leakage current, and $J_S$, and increase of Schottky barrier height. We suggest that the post-annealing in AlGaN/GaN Schottky contacts induces passivation effect, contributing to the device performance improvement in AlGaN/GaN heterostructures. XPS analysis results showed that unintentional oxide layer on the free AlGaN surface is formed by PGA. It is suggested that the thin oxide layer can act as a passivation layer to minimize electron injection from the gate during HEMT operation.

Third, two models for quantitatively characterizing trapping effect in AlGaN/GaN HEMTs were presented based on 0.2 μs pulsed $I-V$ characteristics. It was demonstrated that the current collapse due to electron trapping can be analyzed in terms of various device parameters in AlGaN/GaN HEMTs. It was shown that a higher negative electric field between gate and drain contacts cause a larger current dispersion due to trapping of more electrons, leading to a higher $V_T$ shift in the positive direction, a longer effective gate length, and smaller parasitic resistances. Electron drift velocity characteristics also showed that drift velocity at a higher $V_{GS}$ is lower due to more interface roughness scattering and the thermal effect especially at high current operation region even in 0.2 μs pulsed $I-V$ characteristics.
Finally, it is suggested that our methods can be applied for AlGaN/GaN HEMT modeling in presence of trapping effects for evaluation of new-introduced device/growth techniques, monitoring of device fabrication process, and, potentially, circuit applications.

6.2 Future work

Optimization of AlGaN/GaN HEMT Modeling in presence of traps

In this work, AlGaN/GaN HEMT modeling has been performed in the linear region of $I-V$ characteristics. Our proposed model seems to be perfect in the low drain voltage range but a correction factor is needed in the high-drain voltage linear region. That is why additional critical fields ($E_{C,\text{eff}}$) is introduced for a best fit in the high $V_{DS}$ region while a constant $E_C$ makes our field-dependent mobility model working very well in the low $V_{DS}$ range. The $E_C$ value is close to the critical value for the theoretical maximum drift velocity but $E_{C,\text{eff}}$ values have to be varied with $V_{GS}$ since saturation velocity in drift velocity characteristics is observed at a lower lateral field for a lower $V_{GS}$. To determine better $E_{C,\text{eff}}$ values, a HEMT model has to match saturation velocity on the onset of the saturation at each $V_{GS}$ to the ending drift velocity in the linear region. At this moment, it is not sure whether constant saturation velocity is good for HEMT modeling since thermal effects are observed in high voltage/high-current region. In addition, the
extracted device parameters in the linear region may not be properly applied to the saturation region. Gate-length modulation has also been observed in the saturation region. Thus, further investigations for optimization of HEMT model are required in both linear and saturation regions.

**HEMT modeling with Different geometry HEMTs**

So far, single geometry HEMTs have only been characterized for HEMT modeling with trapping effects, the extracted device parameters with adjusted series resistance values are expected to be different from actual device parameters. Thus, more accurate characterization of active traps requires different geometry HEMTs to extract the actual device parameters of $R_S$, $R_D$, $\mu_i, LOW$, $\theta_i, LOW$, and $L_{Gi,eff}$ using modified SJ methods or non-linear fitting methods described in Chapter 5. In addition, it should be checked whether our assumption (Eq. 5–10) for a rational form of $I–V$ relationship is reasonable by characterization of both very long-gate HEMTs and sub-micro gate HEMTs. Therefore, characterization with different geometry HEMTs will refine the proposed HEMT model.
Passivation effects on AlGaN/GaN HEMTs in terms of device parameters

Introduction of dielectrics/passivation layers has been considered to be inevitable to achieve high reliable AlGaN/GaN HFETs. This is because of highly sensitive surface and high dislocation density in AlGaN/GaN HEMT structures although material growth techniques have been advanced. The dielectrics/passivation layers such as PECVD-Si$_3$N$_4$ and ALD-A$_2$O$_3$ make interface states more stable by physically separate between the sensitive AlGaN surface and environments. More importantly, electron injection from the gate is suppressed. However, current dispersion cannot be removed perfectly especially under high power operation. Using our methodologies for trap characterization, passivated AlGaN/GaN HEMT will be analyzed to evaluate trap activity in terms of device parameters. Through this study, the passivation process can be optimized for high-performance HEMTs.

Development of novel HEMT structures

Currently, field-plate HEMTs have showed the best performance in output power and reliability compared with various device structures since both less current dispersion and high breakdown voltage are achieved. However, increased parasitic capacitance causes decreased power gain. We plan to develop novel HEMT structures such as floating-gate HEMTs to minimize current dispersion and obtain high breakdown voltage.
A very short floating gate can be formed near the gate edge to increase the barrier against electron injected from the actual gate. It is also expected that lateral electric field can be mitigated so that a high breakdown voltage can be achieved while the channel conductance may degrade a little.
References


C. P. Baylis, II and L. P. Dunleavy, "Understanding pulsed IV measurement waveforms," in *Electron Devices for Microwave and Optoelectronic Applications*, 192


Appendix A Model equation derivation

A.1 Derivation of model equation for zero drain bias output conductance method

The following equation is a general I–V relationship of FETs including parasitic resistances and field-dependent mobility.

\[
I_{D_i} = \frac{K_w}{2} \left[ V_{DS} - I_{D_i} (R_{Di} - R_{Si}) \right] \left[ V_{DS} - I_{D_i} R_{Ti} \right] \left[ 1 + \theta_i (V_{DS} - I_{D_i} R_{Ti}) \right] \left[ 1 + \eta_i (V_{DS} - I_{D_i} R_{Ti}) \right]^{\eta_i}
\]  \hspace{1cm} (A-1)

For simplicity, we assume that \( n = 1 \). Then, Eq. (B-1) can be rewritten as:

\[
I_{D_i} = \frac{K_w}{2} \left[ V_{DS} - I_{D_i} (R_{Di} - R_{Si}) \right] \left[ V_{DS} - I_{D_i} R_{Ti} \right] \left[ 1 + \theta_i (V_{DS} - I_{D_i} R_{Ti}) \right] \left[ 1 + \eta_i (V_{DS} - I_{D_i} R_{Ti}) \right] \]  \hspace{1cm} (5-7)

Note that the lateral field effect on the channel mobility in Eq. (A-1) and Eq. (5-7) may not be applicable as in Model 2 (\( E_{Lateral} \geq 10 \text{ kV/cm for } V_{DS} \geq 0.2 \)) since we are looking at a very low lateral field region. Nevertheless, since we are dealing with zero-voltage drain bias, the lateral field effect is not important or is negligible. Eq. (5-7) can be the same form as the long-channel I–V relationship of the linear region. By differentiating Eq. (5-7) without \( [1 + \eta_i (V_{DS} - I_{D_i} R_{Ti})] \), it is reduced to Eq. (A-2) since both \( V_{DS} \) and \( I_D \) are zero.
\[
\frac{\partial I_{Di}}{\partial V_{DS}} = \frac{K_{0i}}{2}\left[1 - \frac{\partial I_{Di}}{\partial V_{DS}}(R_{Di} - R_{Si})\right](V_{DS} - I_{Di}R_{T}) + \frac{K_{0i}}{2}\left[V_{GS} - \frac{1}{2}(V_{DS} - I_{Di}(R_{Di} - R_{Si}))\right]\left[1 - \frac{\partial I_{Di}}{\partial V_{DS}}R_{Si}\right]
\]

\[
= \frac{K_{0i}\left(V_{GS} - \frac{1}{2}(V_{DS} - I_{Di}(R_{Di} - R_{Si}))\right)(V_{DS} - I_{Di}R_{T}) - \theta\frac{\partial I_{Di}}{\partial V_{DS}}R_{Si}}{1 + \theta(V_{GS} - I_{Di}R_{Si})}
\]

\[
= \frac{K_{0i}V_{GSi}\left[1 - \frac{\partial I_{Di}}{\partial V_{DS}}R_{T}\right]}{1 + \theta V_{GSi}}
\]

(A–2)

Then, if Eq. (B–2) is rearranged for \(\partial I_{Di}/\partial V_{DS} = g_D\), Eq. (5–8) is derived.

\[
\frac{\partial I_{Di}}{\partial V_{DS} \text{ at } V_{GS} = 0} = \frac{K_{0i}}{1}\left[\frac{K_{0i}(R_{Di} + \theta)V_{GT}}{R_{Di} + \theta} + c_iV_{GS} + b_i\right] = \frac{c_iV_{GS} + b_i}{a_i}
\]

(5–8)

Even with consideration of \([1 + \eta(V_{DS} - I_{Di}R_{Di})]^{1/n}\), we can deduce the same equation of Eq. (5–8) since \(\partial \eta/\partial V_{DS}\) is expected to negligible as in Model 2.

A.2. Derivation of current-voltage equation in a form of rational function

Current-voltage relationship in AlGaN/GaN HEMTs at \(V_{DS,LOW}\) using newly-introduced device parameters such as \(\mu_{0i,LOW}, \theta_{i,LOW}, \text{ and } K_{0i,LOW}\) by assuming that \([1 + \eta(V_{DS,LOW} - I_{Di}R_{Di})]^{1/n}\) is equal to 1 at a specific fixed low drain voltage \(V_{DS,LOW}\) is expressed by Eq. (A–3)

\[
I_{Di} \approx \frac{K_{0i,LOW}\left[V_{GT} - \frac{1}{2}(V_{DS,LOW} - I_{Di,LOW}(R_{Di} - R_{Si}))\right]\left[V_{DS,LOW} - I_{Di,LOW}R_{Di}\right]}{1 + \theta\left(V_{GT} - I_{Di,LOW}R_{Si}\right)}
\]

(A–3)

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Eq. (A–2) representing current-voltage relationship in AlGaN/GaN HEMTs can be rewritten as the following equation:

\[
\left[ \frac{\theta_{i,\text{LOW}}}{K_{0i,\text{LOW}}} R_{Si} + \frac{1}{2} \left( R_{Si}^2 - R_{Di}^2 \right) \right] I_{D_i,\text{LOW}} - 2 \left( \frac{1}{K_{0i,\text{LOW}}} + V_{GT_i} \left[ \frac{\theta_{i,\text{LOW}}}{K_{0i,\text{LOW}}} + R_{Ti} \right] - V_{DS,\text{LOW}} R_{Di} \right) \right] I_{D_i} I_{D_i,\text{LOW}}
+ V_{DS,\text{LOW}} \left( V_{GT_i} - \frac{1}{2} V_{DS,\text{LOW}} \right) = 0 \quad (A-4)
\]

There exist two second-order effects in Eq. (A–4) due to series resistance. In a quadratic form of Eq. (A–4) with respect to \( I_{D,\text{LOW}} \), the first term is considered to be negligible compared with the third term based on the assumption of Eq. (5–11). Then, Eq. (A–4) can be reduced to Eq. (5–10) as follows:

\[
I_{D_i} = \frac{K_{0i,\text{LOW}} \left( V_{GS_i} - V_{Ti} - 1/2 V_{DS} \right) V_{DS}}{\left[ \left( \theta_{i,\text{LOW}} + K_{0i,\text{LOW}} R_{Ti} \right) V_{GS_i} - V_{Ti} \right] + 1 - K_{0i,\text{LOW}} V_{DS} R_{Di}} = \frac{c_i V_{GS_i} + b_i}{V_{GS_i} + a_i} \quad (5–10)
\]

\[
A_i = \theta_{i,\text{LOW}} + K_{0i,\text{LOW}} R_{Ti}, \quad a_i = -V_{Ti} + \frac{1 - K_{0i,\text{LOW}} V_{DS} R_{Di}}{A_i}, \quad b_i = \frac{K_{0i,\text{LOW}} \left( V_{Ti} + 1/2 V_{DS} \right) V_{DS}}{A_i},
\]

and \( c_i = \frac{K_{0i,\text{LOW}} V_{DS}}{A_i} \).

Eq. (5–10) can be applicable to different QB cases demonstrated in the main text. Note that only one second-order effect incorporated in the effective mobility or gain factor is assumed to be neglected. The other second-order effect from the multiplication of the intrinsic gate and drain voltages is essentially included in Eq. (5–10) but is cancelled out in the second-order term of the drain current since \( R_S = R_D \) for both QB0, QB1, and QB3.
The remaining effect of the multiplication is reflected in the denominator in Eq. (5–10) as a first-order effect \([K_0'V_{DS}R_D \text{ or } V_{DS}R_D]\).

A.3. \(L_{Gi,eff}/L_{G0,eff}\) extraction by derivatives of total resistance \((R_{mi})\) based on Shift and Ratio method

Using Eq. (A–3) or Eq. (5–10) representing current-voltage relationship in AlGaN/GaN HEMTs, total resistance \((R_{mi})\) at \(V_{DS,LOW}\) for \(V_{GTi} \gg I_{Di,LOW}R_{Si}\) except for QB2 can be written as:

\[
R_{mi} = R_{Si} + R_{Di} + \frac{L_{Gi,eff}}{\mu_{i,LOW}C_{AlGaN}W_G(V_{GS} - V_{Ti} - 1/2V_{DS,LOW})} \\
= 2R_{Si} + \frac{L_{Gi,eff}(1 + \theta_{i,LOW}V_{GTi})}{\mu_{i,LOW}C_{AlGaN}W_G(V_{GTi} - 1/2V_{DS,LOW})} \quad (A-5)
\]

Then, the derivative of \(R_{mi}\) with respect to \(V_{GSi}\) can be obtained as:

\[
\frac{\partial R_{mi}}{\partial V_{GSi}} = -\frac{L_{Gi,eff}}{\mu_{i,LOW}C_{AlGaN}W_G} \frac{1/2\theta_{i,LOW}V_{DS,LOW} + 1}{(V_{GTi} - 1/2V_{DS,LOW})^2} \quad (5-13)
\]

As illustrated in the main text, when SR method is directly applied to the measured data for QB1 and QB3, we can determine the ratio of \(L_{Gi,eff}/L_{G0,eff}\) by comparing the derivatives of the measured \(R_{mi}\) at the same \(V_{GT}\) for both QBi and QB0. First, the measured \(R_{m0}\) values are shifted by \(\delta_i\) to make \(V_{GTi}\) equal to \(V'_{GT0} = V_{GT0} - \delta_i\) where \(\delta_i = V_{Ti} - V_{T0}\) is the difference between \(V_{Ti}\) and \(V_{T0}\). Since \(\mu_{i,LOW}\) values are assumed to be equal for both QB0
and $Q_B$, the derivative of the measured $R_{mi}$ divided by that of the shifted $R_{m0}$ turns out to be $\alpha_i$ as shown in Eq. (A–6) where $\delta_i = V_{Ti} - V_{T0}$ is the difference between $V_{Ti}$ and $V_{T0}$.

\[
\frac{\partial R_{mi}(V_{GT})}{\partial V_{GSi}} \frac{\partial R_{m0}(V_{GT0} - \delta_i)}{\partial V_{GS0}} = \left[ \frac{L_{Gi,eff}}{\mu_{0,LOW} C_{AlGaN} W_G} \frac{1/2 \theta_{i,LOW} V_{DS,LOW} + 1}{(V_{GSI} - V_{Ti} - 1/2 V_{DS,LOW})^2} \right] \\
\left[ \frac{L_{GO,eff}}{\mu_{0,LOW} C_{AlGaN} W_G} \frac{1/2 \theta_{0,LOW} V_{DS,LOW} + 1}{(V_{GSO} - V_{T0} - \delta_i - 1/2 V_{DS,LOW})^2} \right] = \left[ \frac{L_{Gi,eff}}{L_{GO,eff}} \right] \frac{1/2 \theta_{i,LOW} V_{DS,LOW} + 1}{1/2 \theta_{0,LOW} V_{DS,LOW} + 1} = \alpha_i \quad (A–6)
\]

In this case, we have to handle the whole measured data in the proper range of $V_{GS}$ with one more mathematical treatment after $V_T$ extraction by non-linear curve fitting to determine the effective gate length ratio.

Alternatively, another equivalent derivative of $R_{mi}$ can be derived from the fitting rational function of Eq. (5–10) as follows:

\[
\frac{\partial R_{mi}}{\partial V_{GS}} = \frac{V_{DS,LOW}}{c_i^2} \frac{b_i - a_i c_i}{(V_{GS} + b_i / c_i)^2} \quad (A–7)
\]

Again, by taking the ratio of $R_{mi}$ ratio between $Q_B$ and $Q_B0$ using Eq. (A–7), we can derive a simple formula consisting of fitting parameters only as in Eq. (A–8).
\[
\frac{\partial R_{mi}(V_{GSi})}{\partial V_{GSi}} \left/ \frac{\partial R_{m0}(V_{GS0} - \delta_i)}{\partial V_{GS0}}\right. = \alpha_i
\]

\[
= \left[ \frac{V_{DS,LOW}}{c_i^2 (V_{GSi} + b_i / c_i)^2} \right] \left[ \frac{V_{DS,LOW}}{c_0^2 (V_{GS0} - \delta_i + b_0 / c_0)^2} \right]
\]

\[
= \frac{c_0^2 (b_i - a_i c_i)}{c_i^2 (b_0 - a_0 c_0)}
\]

(B-8)

where \( \delta_i (= V_{Ti} - V_{T0}) \) is equal to \( b_0/c_0 - b_i/c_i \) since \( V_{Ti} = -b_i/c_i - 1/2 V_{DS,LOW} \). Note that \( V_{GSi} + b_i/c_i \) is equal to \( V_{GS0} + b_0/c_0 - \delta_i \) when \( V_{GTi} = V_{GT0} - \delta_i \). Thus, we can calculate the ratio \( L_{Gi,eff} / L_{G0,eff} \) right after \( V_T \) extraction without any further mathematical manipulation of the measured \( I-V \) data.

**A.4 Relationship between \( R_{Si} \) for QB1 and QB3 and \( R_{S0} \) for QB0**

Total resistance \( (R_{mi}) \) for QB1 and QB3 at the same \( V_{GT} \) for QB0 for \( V_{GTi} >> I_{DS,LOW} R_{Si} \) can be rewritten with a fraction of \( \alpha_i \) assuming \( \mu_{i,LOW} \) values are equal for all QBs as:

\[
R_{mi} = R_{Si} + R_{Di} + \frac{L_{Gi,eff}}{\mu_{i,LOW} C_{AlGaN} W_G (V_{GTi} - 1/2 V_{DS,LOW})}
\]

\[
= 2R_{Si} + \frac{\alpha_i \beta_i L_{G0,eff} (1 + \theta_i V_{GTi})}{\mu_{0,LOW} C_{AlGaN} W_G (V_{GTi} - 1/2 V_{DS,LOW})}
\]

(A-9)

where \( \beta_i = \frac{1/2 \theta_i V_{DS,LOW} + 1}{1/2 \theta_i V_{DS,LOW} + 1} \)
where $L_{Gi,\text{eff}} = \alpha_i \beta_i L_{G0,\text{eff}}$. By subtracting $R_{m0}$ of Eq. (A–5) multiplied by ($\alpha_i$) from $R_{mi}$ at the same $V_{GT}$ (i.e., $V_{GTi} = V_{GT0}$), the following equation can be obtained

$$R_{mi}(V_{GTi}) - \alpha_i R_{m0}(V_{GT0}) = 2(R_{Si} - \alpha_i R_{S0}) + \frac{L_{Gi,\text{eff}}}{\mu_0 C_{AIGA\,N} W_G} \left( (1 + \theta_i V_{GTi}) - \frac{(1 + \theta_0 V_{GT0})}{\beta_i} \right)$$

$$= 2(R_{Si} - \alpha_i R_{S0}) + \frac{L_{Gi,\text{eff}}}{\mu_0 C_{AIGA\,N} W_G} \left( \frac{(1 + \theta_i V_{GTi}) V_{GTi} - 1/2 V_{DS,LOW}}{1/2 V_{DS,LOW}} \right)$$

where the ratio of $(1 - 1/\beta_i)$ to $(\theta_i - \theta_0 / \beta_i)$ can be reduced to $-1/2 V_{DS,LOW}$ as follows:

$$\frac{1 - 1/\beta_i}{\theta_i - \theta_0 / \beta_i} = \frac{\beta_i - 1}{\theta_i \beta_i - \theta_0} = \frac{1}{\theta_i} \frac{1/2 \theta_0 V_{DS,LOW} + 1}{1/2 \theta_0 V_{DS,LOW} + 1} = -1$$

$$= \frac{1/2 \theta_0 V_{DS,LOW} - 1/2 \theta_i V_{DS,LOW}}{1/2 \theta_0 V_{DS,LOW} + 1}$$

$$= \frac{1}{1/2 \theta_0 V_{DS,LOW} + \theta_i - 1/2 \theta_i \theta_0 V_{DS,LOW} - \theta_0}{1/2 \theta_0 V_{DS,LOW} + 1}$$

$$= \frac{1/2 V_{DS,LOW} (\theta_0 - \theta_i)}{\theta_i - \theta_0} = -1/2 V_{DS,LOW} \quad (A-11)$$
In addition, Eq. (A−8) can be equated to the modified form of Eq. (5−10) as follows:

\[ R_{mi} = R_{Si} + R_{Dr} + \frac{L_{Gi,\,eff}}{C_{AlGa} W} \left( V_{GT} - 1/2 V_{DS,\,LOW} \right) = V_{DS,\,LOW} \frac{V_{GSi} + a_i}{c_i V_{GSi} + b_i} \quad (A−12) \]

Again, by subtracting \( R_{m0} \) of Eq. (A−12) multiplied by \( \alpha_i \) from \( R_{mi} \) at the same \( V_{GT} \), (i.e., \( V_{GS0} = V_{GSi} - \delta_i \)), the following equation can be obtained using Eq. (A−8) and Eq. (A−12).

\[ R_{mi}(V_{GT}) - \alpha_i R_{m0}(V_{GT0} - \delta_i) = R_{mi}(V_{GS0}) - \alpha_i R_{m0}(V_{GS0} - \delta_i) \]

\[ = \frac{V_{DS}}{c_i c_0} \left[ c_0 V_{GSi} + a_i c_0 - \alpha_i c_i V_{GSi} - \delta_i \right] \left( V_{GSi} - \delta_i \right) + a_i c_i \left( V_{GSi} + b_i / c_i \right) \]

\[ = \frac{V_{DS}}{c_i c_0} \left[ c_0 - \alpha_i c_i \right] V_{GSi} + a_i c_0 - \alpha_i \left( -c_i b_i / c_0 + b_i + a_i c_i \right) \]

\[ = \frac{V_{DS}}{c_i c_0} \left[ c_0 - \alpha_i c_i \right] V_{GSi} + b_i / c_i \]

\[ = \frac{V_{DS}}{c_i c_0} \left[ c_0 - \alpha_i c_i \right] \]

\[ (A−13) \]

where \( V_{GS0} = V_{GSi} - \delta_i \) equals \( V_{GSi} + b_i / c_i \), and \( \left[ -(c_0 - \alpha_i c_i) b_i / c_i + a_i c_0 - \alpha_i(-c_i b_i / c_0 + b_i + a_i c_i) \right] \) turns out to be zero using Eq. (A−8). From Eq. (A−12) and Eq. (A−13), the expression of \( R_{Si} \) showing relationship between \( R_{S0} \) for QB0 and \( R_{S1} \) for QB1 and 3 can be expressed as:

\[ R_{Si} = \alpha_i R_{S0} + \frac{1}{2} \left[ \frac{V_{DS,\,LOW} \left( c_0 - \alpha_i c_i \right)}{c_i c_0} \right] - \frac{L_{Gi,\,eff} \theta_i - \theta_0 / \beta_i}{\mu_{LOW} C_{AlGa} W} \]  

\[ (A−14) \]
For simplicity, assuming $\theta_i = \theta_0$ so that $\beta_i = 1$, Eq. (A–14) can be reduced to Eq. (A–15).

$$R_{Si} \approx \alpha_i R_{S0} + \frac{1}{2} \left[ \frac{V_{DS}(c_0 - \alpha_i c_i)}{c_i c_0} \right] \quad (A-15)$$

In fact, the first term in the bracket of Eq. (B–14) is much larger than the second term based on the $K_{0,LOW}$ and $\theta_{i,LOW}$ values in Table 5.5. This equation is the same expression of Eq. (5–15) as follows:

$$2(R_{Si} - \alpha_i R_{S0}) \approx \frac{V_{DS}(c_0 - \alpha_i c_i)}{c_0 c_i} \quad (5-15)$$