Effect of Electric Field On Electron Mobility in Sub-100 nm InAlN/GaN High Electron Mobility Transistors

Peng Cui (pcui@sdu.edu.cn)  
Shandong University

Yuping Zeng  
University of Delaware

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Effect of electric field on electron mobility in sub-100 nm InAlN/GaN high electron mobility transistors

Peng Cui\textsuperscript{1,*} & Yuping Zeng\textsuperscript{2}

Abstract

Electron mobility is important for electron velocity, transport current, output power, and frequency characteristics. In conventional mobility extraction methods, electron mobility is usually extracted directly from the measured gate capacitance ($C_{\text{G}}$) and current-voltage characteristics. When device gate length ($L_{\text{G}}$) scales to sub-100 nm, the determination of $C_{\text{G}}$ becomes more difficult not only for the measure equipment but also the enhanced effect from parasitic capacitance. Here in this paper, the $C_{\text{G}}$ extracted from high-frequency small-signal equipment circuit is used for the InAlN/GaN high electron mobility transistors (HEMTs). Electron mobility of the device with $L_{\text{G}}$ of 60-nm under $V_{\text{DS}}$ of 0.1 V and 10 V is extracted using two-dimensional scattering theory, respectively. The obtained results show that under a high electric field, the electron temperature ($T_{\text{e}}$) and addition polarization charges ($\Delta \sigma$) increase, resulting in the enhanced polar optical phonon (POP) as well as polarization Coulomb field (PCF) scatterings and degradation of the electron mobility. This study makes it possible to improve the electron mobility by reducing $T_{\text{e}}$ and $\Delta \sigma$ for the InAlN/GaN HEMTs application. AlGaN/GaN heterostructure field-effect transistors with different gate lengths were fabricated. Based on the chosen of the Hamiltonian of the system and the additional polarization charges, two methods to calculate PCF scattering by the scattering theory were presented. By comparing the measured and calculated source-
drain resistances, the influence of the different gate lengths on the PCF scattering potential was confirmed.
should be addressed to P.C. (email: pceu@sdu.edu.cn).
Introduction

GaN-based high-electron-mobility transistors (HEMTs) indicate great potential for millimeter-wave power applications\textsuperscript{1-5}. Electron mobility plays an important role in electron velocity, high-frequency, and output power in GaN HEMTs\textsuperscript{6-9}. As we know, many works on electron mobility and carrier scattering model have been reported\textsuperscript{10-14}. Polar optical phonon (POP) and polarization Coulomb field (PCF) scattering have been demonstrated as the main scattering mechanisms in GaN HEMTs\textsuperscript{10,14,15}. Electron density ($n_{2D}$) and electron temperature ($T_e$) dominate POP scattering\textsuperscript{10,14}. Addition polarization charges ($\Delta \sigma$) and device dimension (gate length $L_G$, source-drain spacing $L_{SD}$, et al.) present significant influence on PCF scattering\textsuperscript{12,15,16}. In conventional mobility study, the devices with micrometer gate length are usually used\textsuperscript{8,17,18}. As devices scale down, the electric field in the channel will increase. The channel electrons can accurate under a high electric field and then $T_e$ increases. Scaling down also changed the device dimension and the effect of $\Delta \sigma$ on small device dimension becomes more significant. Hence, POP and PCF scatterings will be changed with the electric field and device scaling down. But to the best of our knowledge, there are few reports about it. Therefore, extract and study the electron mobility in GaN HEMTs with nanometer $L_G$ is meaningful.

In general, the electron mobility extraction is based on the directly measured gate capacitance ($C_G$) and current-voltage characteristic\textsuperscript{8,17,18}. As devices scale down, the accurate capacitance of small $L_G$, especially nanometer $L_G$, is difficult to obtained by directly measurement. In this paper, high-frequency small-signal equipment circuit are used for the $C_G$ extraction. The electron mobility of the InAlN/GaN HEMTs with $L_G$ of 60 nm under drain-source ($V_{DS}$) of 0.1 V and 10 V is extracted with two-dimensional scattering theory. The obtained results show that under high electric field, the increased
$T_e$ and $\Delta \sigma$ enhance POP and PCF scatterings, resulting in degradation of electron mobility. This makes it possible to further improve device performance for the InAlN/GaN HEMTs application.

**Results and discussion**

**A. Low-Field Electron Mobility**

![Figure 1. Schematic of the fabricated InAlN/GaN HEMT on Si substrate.](image)

Figure 1 shows the schematic of the fabricated InAlN/GaN HEMT on Si substrate. Devices with source-drain distance ($L_{SD}$) of 2 $\mu$m, gate length ($L_G$) of 60 ~ 150 nm, and gate width ($W_g$) of $20 \times 2$ $\mu$m were fabricated. To extract electron mobility, the determination of the electron density ($n_{2D}$) is very important. In conventional mobility extraction methods, $n_{2D}$ is usually extracted directly from the measured gate capacitance ($C_G$) of the device with a micrometer gate as $8,17,18$. For the devices with sub-100 nm $L_G$, not only the small gate length requires higher accuracy on the capacitance measurement equipment, the effect from the gate parasitic capacitance ($C_{Gext}$) on the nanometer gate cannot be ignored$^{19-21}$. The T-shape gate with a larger gate head also increases $C_{Gext}$, as
shown in Figure 2\textsuperscript{19-21}. Therefore, the extraction of $n_{2D}$ from the directly measured gate capacitance is not applicable for the sub-100 nm devices.

![Figure 2. Schematic of $C_{\text{Gint}}$ and $C_{\text{Gext}}$ under the gate region in InAlN/GaN HEMT.](image)

Another possible method to obtained $C_G$ is from high-frequency $S$-parameters. Figure 3 shows the classical 16-element equivalent-circuit model for InAlN/GaN HEMTs\textsuperscript{22,23}. In the model, $C_G$ is divided into the gate-drain capacitance ($C_{GS}$) and gate-source capacitance ($C_{GS}$), which can be obtained from the measured high-frequency $S$-parameter\textsuperscript{22,23}.

![Figure 3. Classical 16-element equivalent-circuit model for InAlN/GaN HEMT.](image)
Figure 4. (a) $C_G$ as a function of $V_{GS}$ at $V_{DS} = 0.1$ V for the InAlN/GaN HEMTs with $L_G$ of 60, 70, 80, 100, 130, 150 nm, respectively. (b) $C_G$ as a function of $L_G$ under different $V_{GS}$. Scatters are the measured results and lines are the fitting curves.

Figure 5. $C_{Gint}$ (left) and $n_{2D}$ (right) as a function of $V_{GS}$ at $V_{DS} = 0.1$ V for the InAlN/GaN HEMT with $L_G = 60$ nm.
In this study, the device $S$-parameter is measured from 1 to 50 GHz using an Anritsu MS4647B vector network analyzer. The gate-source voltage ($V_{GS}$) is changed from -6 to 1 V with 0.5 V step and the drain-source voltage ($V_{DS}$) is fixed at 0.1 V. With the measured $S$-parameters, $C_{GS}$ and $C_{GD}$ as a function of $V_{GS}$ can be obtained with the classical 16-element equivalent-circuit model. Then $C_G$ ($C_G = C_{GS} + C_{GD}$) as a function of $V_{GS}$ under $V_{ds} = 0.1$ V can be plotted, as shown in Figure 4(a). Here the $C_G$ of the InAlN/GaN HEMTs with $L_G$ of 60, 70, 80, 100, 130, 150 nm are obtained. Figure 4(b) shows $C_G$ as a function of $L_G$ under different $V_{GS}$. Scatters are the measured results and lines are the fitting curves. The measured $C_G$ is linearly dependent upon $L_G$, in which the Y-intercept corresponds to the $C_{Gext}$. By subtracting $C_{Gext}$, the intrinsic gate capacitance ($C_{Gint}$) can be obtained. Figure 5 shows a typical result of $C_{Gint}$ versus $V_{GS}$ for the InAlN/GaN HEMTs with $L_G = 60$ nm. Integrating $C_{Gint}$ with $V_{GS}$, $n_{2D}$ as a function of $V_{GS}$ is obtained and depicted in Figure 5.

![Figure 6](image.png)

Figure 6. Transfer characteristic at $V_{DS} = 0.1$ V for the InAlN/GaN HEMT with $L_G = 60$ nm.
Figure 6 shows the measured transfer characteristic of the InAlN/GaN HEMTs with $L_G = 60$ nm under $V_{ds} = 0.1$ V. The total resistance ($R$) can be extracted from the transfer characteristic, which includes the source-drain material resistance ($R_{SD}$) and source/drain ohmic contact resistance ($R_C$). The 2DEG electrons under the gate region is modulated with the gate voltage, but that of the non-gate region (access region) is unchanged. Therefore $R_{SD}$ can be written as\textsuperscript{15,24}

$$R_{SD} = R_G + R_{\text{access}} = \frac{L_G}{n_{2D}qW_c\mu_G} + \frac{L_{GD}}{n_{2D0}qW_c\mu_{\text{access}}}.$$ \hspace{1cm} (1)

Here $R_G$ and $R_{\text{access}}$ are the resistances under the gate region and under the access region, respectively. $L_{GS}$ and $L_{GD}$ are the gate-source and gate-drain distances, respectively. $q$ is the electron charge. $n_{2D}$ is the electron density under the gate region, as shown in Figure 5. $n_{2D0}$ is the electron density under the access region, which is the same with the electron density under the gate region at $V_{GS} = 0$ V. $\mu_G$ and $\mu_{\text{access}}$ are the electron mobility under the gate region and under the access region, respectively.
Figure 7. (a) Electron mobility under the gate region ($\mu_G$) limited by different scattering mechanisms as a function of $V_{GS}$ at $V_{DS} = 0.1$ V. (b) Electron mobility under the access region ($\mu_{\text{access}}$) limited by different scattering mechanisms as a function of $V_{GS}$ at $V_{DS} = 0.1$ V.

In InAlN/GaN HEMTs, the main scattering mechanisms include polar optical phonon (POP), polarization Coulomb field (PCF), acoustic phonon (AP), interface roughness (IFR), and dislocation (DIS) scatterings\textsuperscript{10,14,15}. Therefore, $\mu$ can be obtained from

\[
\frac{1}{\mu} = \frac{1}{\mu_{\text{POP}}} + \frac{1}{\mu_{\text{PCF}}} + \frac{1}{\mu_{\text{AP}}} + \frac{1}{\mu_{\text{IFR}}} + \frac{1}{\mu_{\text{DIS}}}.
\]  

Here $\mu_{\text{POP}}$, $\mu_{\text{PCF}}$, $\mu_{\text{AP}}$, $\mu_{\text{IFR}}$, and $\mu_{\text{DIS}}$ are the electron mobility limited by POP, PCF, AP, IFR, and DIS scatterings, respectively, which can be obtained by using two-dimensional scattering theory\textsuperscript{10,15}. Hence $\mu_G$ and $\mu_{\text{access}}$ can be determined and is shown...
in Figure 7. It is significant that POP and PCF scatterings demonstrate the electron mobility. POP scattering is relevant with $n_{2D}$ and electron temperature ($T_e$). Both increase can enlarge the collision probability between the carriers and lattice atoms, resulting in enhanced POP scattering\textsuperscript{10,14}. Here $V_{DS} = 0.1$ V, channel electric field is very low. $T_e$ is at the temperature and is unchanged. $n_{2D}$ is the only factor that affects POP scattering. Under the gate region, $n_{2D}$ increases with $V_{GS}$ and enhances the POP scattering. PCF scattering comes from the non-uniform of the polarization charges in the InAlN barrier\textsuperscript{12,25}. Due to the converse piezoelectric effect, the applied gate voltage can change the polarization charges of the InAlN barrier under the gate region and causes the addition polarization charges ($\Delta \sigma$)\textsuperscript{16,26}. $\Delta \sigma$ can cause the PCF scattering potential and result in PCF scattering. Here a more negative $V_{GS}$ causes more $\Delta \sigma$ under the gate region, and leads to larger PCF scattering. Therefore, PCF scattering is enhanced when $V_{GS}$ is shifted to more negative. It can be seen that at $V_{GS} < -2$ V, PCF scattering demonstrates the total electron mobility. With $V_{GS}$ increases to more than -2 V, the increased $n_{2D}$ causes that POP scattering plays a lead role on electron mobility. Then the total $\mu_G$ presents a tread that it increases to a peak and then decreases with the increase of $V_{GS}$.

Under the access region, the electron density is unchanged with $V_{GS}$. Therefore, POP, AP, IFR, DIS scatterings are not affected with $V_{GS}$. As the gate voltage increases, $\Delta \sigma$ decreases and PCF scattering is weakened. Because $L_G$ is 60 nm and $L_{SD} = 2 \mu$m, the effect of $\Delta \sigma$ under the small gate region on the large access region is weak, causing PCF scattering of $\mu_{\text{access}}$ is weaker than that of $\mu_G$. 

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Figure 8. Calculated $R_G$, $R_{\text{access}}$, calculated $R_{SD}$ (line), and measured $R_{SD}$ (scatters) as a function of $V_{GS}$.

Based on the extracted $\mu_G$ and $\mu_{\text{access}}$ in Figure 7, $R_G$, $R_{\text{access}}$ and $R_{SD}$ can be calculated by using (1), as plotted in Figure 8. The measured $R_{SD}$ is extracted from transfer characteristic in Figure 6. It is shown that the calculated and measured $R_{SD}$ present a good consistence, confirming the accurate of the two-dimensional electron system scattering theory.

B. High-Field Electron Mobility
Figure 9. (a) $C_G$ as a function of $V_{GS}$ at $V_{DS} = 10$ V for the InAlN/GaN HEMTs with $L_G$ of 60, 70, 80, 100, 130, 150 nm, respectively. (b) $C_G$ as a function of $L_G$ under different $V_{GS}$. Scatters are the measured results and lines are the fitting curves.

Figure 10. $C_{Gint}$ (left) and $n_{2D}$ (right) as a function of $V_{GS}$ at $V_{DS} = 10$ V for the InAlN/GaN HEMT with $L_G = 60$ nm.
The $S$-parameter with frequency of 1 to 50 GHz at $V_{DS} = 10$ V are also measured. **Figure 9(a)** shows the extracted $C_G$ as a function of $V_{GS}$ at $V_{DS} = 10$ V for the InAlN/GaN HEMTs with $L_G$ of 60, 70, 80, 100, 130, 150 nm. **Figure 9 (b)** depicts $C_G$ versus $L_G$ under different $V_{GS}$. A linear dependence of $C_G$ upon $L_G$ is also observed under different $V_{GS}$. $C_{ext}$ is obtained from the Y-intercept of the linear fitting curve. Then by subtracting $C_{ext}$, $C_{int}$ as a function of $V_{GS}$ is plotted in **Figure 10**. $n_{2D}$ is calculated with integration of $C_{int}$ with $V_{GS}$. This is also shown in **Figure 10** (see right Y-axis).

**Figure 11.** (a) Output and (b) transfer characteristics at $V_{DS} = 10$ V for the InAlN/GaN HEMTs with $L_G = 60$ nm.
Figure 12. (a) $v_e$ (left) and $E$ (right) as a function of $V_{GS}$. (b) $UI/N_e$ (left) and $T_e$ (right) as a function of $V_{GS}$.

Figure 13. (a) Electron mobility under the gate region ($\mu_G$) limited by different scattering mechanisms as a function of $V_{GS}$ at $V_{DS} = 10$ V. (b) Electron mobility under the access region ($\mu_{accsee}$) limited by different scattering mechanisms as a function of $V_{GS}$ at $V_{DS} = 10$ V.
Figure 11(a) shows the output characteristic of the InAlN/GaN HEMT with \( L_G = 60 \) nm. At \( V_{DS} = 10 \) V, the device operates at current saturation region. For the InAlN/GaN HEMT with \( L_G = 60 \) nm, the output current saturation is due to the electron velocity (\( v_e \)) saturation. In this condition, because the drain-source is very high (\( V_{DS} = 10 \) V) and \( L_{SD} = 2 \) \( \mu \)m, the electric field in the drain-source channel, especially in the gate channel region is very high. The high electric field can accurate the electrons to high \( v_e \). The electrons with high \( v_e \) own a high electron temperature (\( T_e \)), which presents significant influence on electron transport\(^{27,28}\). Figure 11(b) plots the measured transfer characteristic at \( V_{DS} = 10 \) V of the same device. With the obtained \( n_{2D} \) in Figure 10 and the drain current \( I_D \) in Figure 11(b), \( v_e \) is obtained from \( I_D = n_{2D} q v_e \). Based on the dependence of \( v_e \) on electric field (\( E \)) in GaN HEMTs, \( E \) can be determined\(^{27}\). Figure 12 depicts \( v_e \) and \( E \) in the gate channel region as a function of \( V_{GS} \). When \( V_{GS} \) increases from -3.5 V to 1 V, \( v_e \) decreases from \( 1.24 \times 10^7 \) cm/s to \( 7.38 \times 10^6 \) cm/s, and \( E \) decreases from 23.99 kV/cm to 9.12 kV/cm. The supplied power per electron \( P_e = E I_D / n_{2D} \) is calculated with the obtained \( E \). Based on the relationship between \( T_e \) and \( P_e \), \( T_e \) can be determined\(^{27,28}\). Figure 13 presents \( P_e \) and \( T_e \) as a function of \( V_{GS} \). As \( V_{GS} \) increases, \( P_e \) decreases from \( 4.79 \times 10^{-8} \) W to \( 1.08 \times 10^{-8} \) W, and \( T_e \) decreases from 521.7 K to 518.7 K. At \( V_{DS} = 0.1 \) V, because the low electric field, electron temperature is at the room temperature (\( T_e = 300 \) K). Compared with \( V_{ds} = 0.1 \) V, \( T_e \) increases from 300 K to ~ 520 K, resulting in an 73% increase of \( T_e \).

With the obtained \( n_{2D} \) and \( T_e \), the electron mobility at \( V_{DS} = 10 \) V can be calculated by using 2D scattering theory. Figure 13 shows the calculated \( \mu_G \) and \( \mu_{access} \) at \( V_{DS} = 10 \) V. POP and PCF scatterings are still the main scattering mechanisms at \( V_{DS} = 10 \) V, which is the same with that at \( V_{DS} = 0.1 \) V. Compared with the electron mobility at \( V_{DS} = 0.1 \) V, \( \mu_{access} \) presents a slight decrease, but \( \mu_G \) shows a large decrease. The influence
of electric field on the electron mobility is discussed in the following part.

C. Influence Electric Field on Electron Mobility

![Figure 14](image)

**Figure 14.** (a) $n_{2D}$ and (b) $E$ as function of $V_{GS}$ under $V_{DS}$ of 0.1 and 10 V.
Figure 15. (a) $\Delta \sigma$ and (b) $T_e$ as function of $V_{GS}$ under $V_{DS}$ of 0.1 and 10 V.

Figure 16. Electron mobility under the gate region ($\mu_G$) limited by POP (POP), PCF scatterings (PCF) and total $\mu_G$ (Total) as a function of $V_{GS}$ under $V_{DS}$ of 0.1 and 10 V, respectively.
Figure 14(a) compares the $n_{2D}$ at $V_{DS} = 0.1$ V and 10 V. At high $V_{DS}$, $n_{2D}$ presents a significant decrease, which results from the improved channel electric potential. Figure 14(b) depicts the channel electric field as a function of $V_{GS}$ and more than 10 times improvement on the electric field is demonstrated. Figure 15 shows $\Delta \sigma$ and $T_e$ as function of $V_{GS}$ under $V_{DS}$ of 0.1 and 10 V and both increases with the increased $V_{DS}$. The increase of $\Delta \sigma$ and $T_e$ enhances PCF and POP scatterings at $V_{DS} = 10$ V, as shown in Figure 16. Therefore, a significant decrease of $\mu_G$ at $V_{DS} = 10$ V is demonstrated.

Conclusions

In summary, $C_G$ extracted from high-frequency small-signal equipment circuit is used for the InAlN/GaN high electron mobility transistors (HEMTs) with sub-100 nm gate length. $\mu$ under $V_{DS}$ of 0.1 V and 10 V are extracted with two-dimensional scattering theory, respectively. Under high electric field, the increased $T_e$ and $\Delta \sigma$ enhances POP and PCF scatterings, resulting in the degradation of electron mobility, which hiding the improvement of the device performance of GaN HEMTs. Hence, in the further study, the method to improve electron mobility by decreasing $\Delta \sigma$ and $T_e$, should be very important for the application of GaN HEMTs.

Methods

Sample fabrication. Figure 1 shows the schematic of the fabricated InAlN/GaN HEMT on Si substrate. The epitaxial structures are grown with metalorganic chemical vapor deposition (MOCVD), which consists of a 2-μm undoped GaN buffer layer, a 4-nm In$_{0.12}$Ga$_{0.88}$N back-barrier layer, a 15-nm GaN channel layer, a 1-nm AlN interlayer, an 8-nm lattice-matched In$_{0.17}$Al$_{0.83}$N barrier layer, and a 2-nm GaN cap layer. Fabrication process started with device mesa isolation by using Cl$_2$-based inductively coupled plasma (ICP) etching. Source and drain ohmic contacts were formed with
Ti/Al/Ni/Au metal stack deposition and annealing at 850˚C for 40s. Finally, T-shaped gate was fabricated with electron beam lithography and Ni/Au deposition. Devices with source-drain distance ($L_{SD}$) of 2 µm, gate length ($L_G$) of 60 ~ 150 nm, and gate width ($W_g$) of $20 \times 2$ µm were fabricated.

**Measurements.** Current-voltage ($I-V$) measurements for the InAlN/GaN HEMTs were performed at room temperature using an Agilent B1500A semiconductor parameter analyzer, and capacitance-voltage ($C-V$) measurements were performed at room temperature using an Agilent B1520A at 1MHz. The S-parameters are taken with Anritsu MS4647B vector network analyzer configured to operate from 1 to 65 GHz.

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**Author contributions**

P. C. and Y. Z. contributed to the research design, experiment measurements, data analysis, and manuscript preparation. All authors reviewed this manuscript.

**Additional information**

**Competing financial interests:** The authors declare no competing interests.

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