The Effect of Adding InGaN Interlayer on AlGaN/GaN Double Channel HEMT for Noise Improvement

Robab Madadi, Saeid Marjani, Rahim Faez, and Seyed Ebrahim Hosseini

Abstract. In this paper, the microwave noise of $Al_{0.3}Ga_{0.7}N$/GaN heterojunction high electron-mobility transistors (HEMTs) with three different structures is investigated by using TCAD extensive simulations. By inserting a 21 nm $Al_{0.05}Ga_{0.95}N$ bottom barrier layer at 14 nm away from the AlGaN/GaN heterointerface, the device shows higher transconductance and lower minimum noise figure (NFmin) than conventional AlGaN/GaN HEMT. In order to further improve the device performance, a new AlGaN/GaN DC-HEMT structure is proposed by inserting a 3 nm $In_{0.1}Ga_{0.9}N$ layer at 6 nm away from the $Al_{0.05}Ga_{0.95}N$/GaN heterointerface. Due to higher carrier density and mobility, AlGaN/GaN DC-HEMT with $In_{0.1}Ga_{0.9}N$ shows higher transconductance and lower NFmin than $Al_{0.3}Ga_{0.7}N$/GaN DC- HEMT.

Keywords: AlGaN/GaN, double channel (DC) HEMTs, InGaN, minimun noise figure (NF_{min}).

1. Introduction

The AlGaN/GaN high electron mobility transistors (HEMTs) have been investigated as they are attractive candidates for high voltage, high-temperature and high power operation at microwave frequencies [1]. Due to the large offset in conduction band and polarization charge induced at the AlGaN/GaN heterostructures, there is a high-density two dimensional electron gas (2-DEG) at the AlGaN/GaN interface [2]. Various investigations have been reported on microwave noise performance of GaN HEMTs in the literature. A. T. Ping et al. reported NF_{min} of 1.06 dB at 10 GHz for AlGaN/GaN HEMTs with 0.25 µm gate length [3]. AlGaN/GaN HEMT with gate lengths less than 0.15 µm achived NF_{min} of 0.6 dB at 10 GHz [4]. NF_{min} for AlGaN/GaN HEMT with gate length of 0.12 µm is shown 1 dB at 18 GHz [5]. H. Sun et al. reported NF_{min} of 1.2 dB at 20 GHz for AlGaN/GaN HEMT with 0.1 gate length [6]. There have been some efforts on enhancing HEMT structures in order to improve their characteristics in the literature [7-10]. $Al_{0.3}Ga_{0.7}N/Al_{0.05}Ga_{0.95}N$/GaN composite-channel HEMT has been reported to improve linearity [7]. This structure showed NF_{min} of 3.3 dB at 10 GHz [8] for 1 µm gate length. J. Liu et al. fabricated AlGaN/GaN/ InGaN/GaN dual hetero structure (DH) HEMT with an InGaN back-barrier aiming at DC and RF improvement [9]. NF_{min} of this transistor with 1 µm gate length is measured about 4dB for E-mode and 5dB for D-mode at 10 GHz [10]. Also, AlGaN-GaN double channel HEMT is reported and showed high current drive, low buffer leakage and fast frequency response [11, 12].

In this paper, a comparative study of three different AlGaN/GaN HEMT architectures in terms of their DC performance and microwave noise characteristics is carried out with TCAD device simulator. Section 2 presents the device structures and band diagram of the three structures. In section 3, the DC characteristics of the structures are presented. In section 4, the microwave noise characteristics are investigated and discussed. Finally, conclusions are made in section 5.

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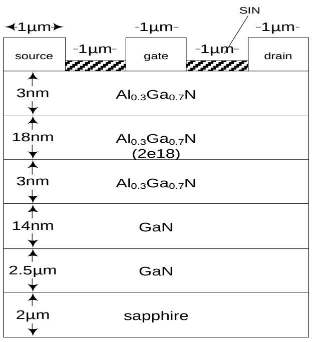
2. Simulated Structures

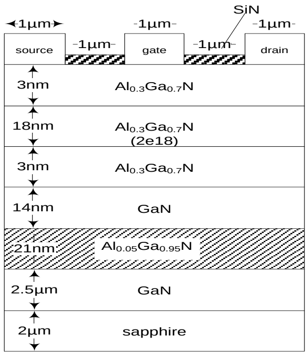
The $Al_{0.3}Ga_{0.7}N$/GaN EMT, $Al_{0.3}Ga_{0.7}N/GaN/Al_{0.05}Ga_{0.95}N$/GaN DC-HEMT [11] and $Al_{0.3}Ga_{0.7}N/GaN/Al_{0.05}Ga_{0.95}N/GaN/In_{0.1}Ga_{0.9}N$/GaN HEMT structures are shown in Fig. 1(a), (b) and (c) respectively. Fig. 1(a) consists of 2 µm sapphire substrates, a 2.5 µm GaN undoped buffer layer, a 14 nm GaN undoped major channel layer, a 3 nm $Al_{0.3}Ga_{0.7}N$ undoped spacer layer, a 18 nm doped (2×10^{18} cm^{-3}) carrier supplier layer and a 3 nm undoped cap layer. Spacer layer reduces impurity scattering and hence prevents mobility degradation of channel electrons. 2-DEG forms in the GaN undoped channel. The devices have a source-gate spacing of L_{sg}=1 µm, gate-drain spacing of L_{gd}=1 µm, a 1 µm gate length. Fig. 1(b) is similar to Fig. 1(a). One difference is insertion of a 21 nm $Al_{0.05}Ga_{0.95}N$ bottom barrier layer. The proposed structure is similar to the fabricated experimental device reported by Wang et al. [11] except that a 3 nm $In_{0.1}Ga_{0.9}N$ layer is inserted as the minor channel as shown in Fig. 1(c).

The band gaps (Eg) of layers and the polarization charge density at the interface of $Al_{0.3}Ga_{0.7}N$/GaN, GaN/ $Al_{0.05}Ga_{0.95}N$, $Al_{0.05}Ga_{0.95}N$/GaN, GaN/$In_{0.1}Ga_{0.9}N$ and $In_{0.1}Ga_{0.9}N$/GaN are calculated based on equations in [13]. The conduction band of the $Al_{0.3}Ga_{0.7}N$/GaN HEMT is plotted in Fig. 2(a). $Al_{0.05}Ga_{0.95}N$ as the bottom barrier layer is located 14 nm below the AlGaN/GaN heterointerface. As shown in Fig. 2(b) the conduction band at the $Al_{0.05}Ga_{0.95}N$/GaN interface falls below the Fermi level and a minor channel can be formed. However, most of the electrons are in the GaN major channel. As shown in Fig. 2(c) the conduction band at the GaN/$In_{0.1}Ga_{0.9}N$ interface falls below the Fermi level and a minor channel is formed. However, most of the electrons are in the GaN major channel. Fig. 2(c) Shows conduction band of $Al_{0.3}Ga_{0.7}N/GaN/AlGaN/GaN/In_{0.1}Ga_{0.9}N$/GaN HEMT.

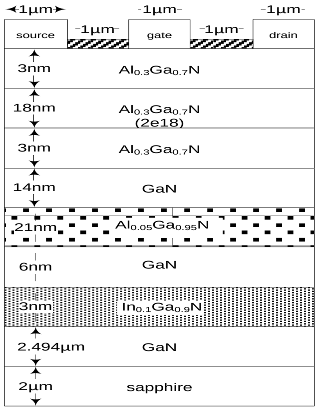
Motivation for adding $In_{0.1}Ga_{0.9}N$ layer is twofold. First,



(a)



(b)



(c)

Fig.1. (a) AlGaN/GaN HEMT structure, (b) AlGaN/GaN DC-HEMT structure [11] and (c) AlGaN/GaN DC-HEMT with InGaN layer structure.

in GaN/GaN results a high polarization charge which increases the channel carrier density. Second, InGaN as a minor channel has higher electron mobility compared to GaN channel, which results higher drain current and transconductance. Moreover, due to higher conduction band discontinuity, this layer prevents carriers to inject into the substrate.

3. DC Performance

The DC characteristics are investigated using Silvaco device simulator. Fig. 3(a) shows the I_{DS}-V_{DS} curve of AlGaN/GaN HEMT. With gate bias of 0 V, the maximum drain current is about 500 mA/mm. The pinchoff voltage of AlGaN/GaN HEMT is about -6.5 V as shown in Fig. 3(d). Also the maximum transconductance is about 110 ms/mm that is plotted in Fig. 3(e).

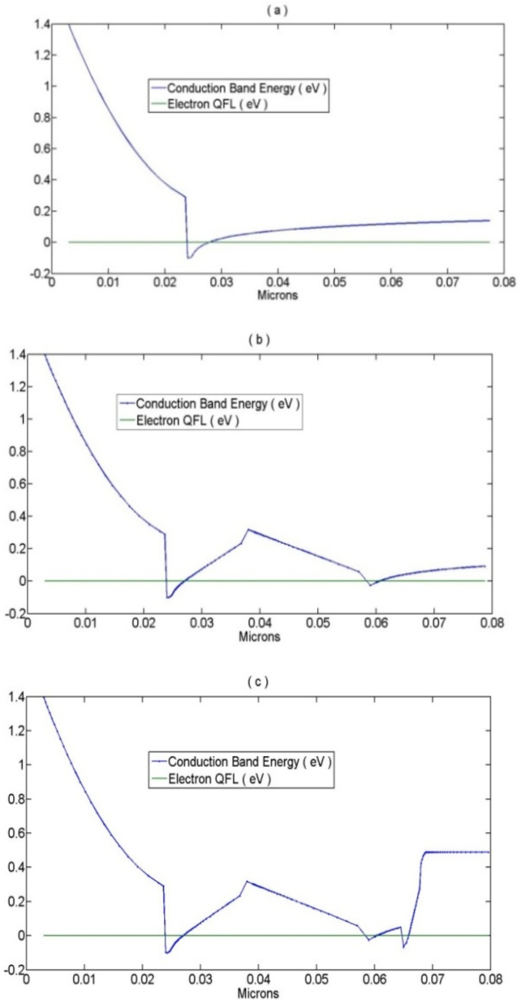


Fig.2. Conduction band of (a) AlGaN/GaN HEMT, (b) AlGaN/GaN DC-HEMT and (c) AlGaN/GaN DC-HEMT with InGaN layer.

Fig. 3(b) shows I_{DS}-V_{DS} curve of AlGaN/GaN/$Al_{0.05}Ga_{0.95}N$/GaN DC-HEMT. The maximum drain current is about 700 mA/mm at V_{GS}=0V that is higher than AlGaN/GaN HEMT. Increase of I_{DS} is because of high polarization charge and mobility. The pinchoff voltage of AlGaN/GaN DC-HEMT is about -7.5 V that is because of high carrier density. Also the maximum transconductance is about 135 ms/mm that is plotted in Fig. 3(e), higher transconductance in this structure than AlGaN/GaN HEMT is because of high polarization charge and high mobility.

Fig. 3(c) shows I_{DS}-V_{DS} curve of AlGaN/GaN DC-HEMT with InGaN layer. High mobility and carrier density cause the drain current as high as 900 mA/mm at V_{GS}=0 V. The pinch off voltage of AlGaN/GaN DC-HEMT with InGaN is about -8 V. Larger pinchoff voltage in DC-HEMT with InGaN is because of GaN minor channel and high polarization charge at the interface of GaN/InGaN. Because of high carrier density this transistor needs high gate voltage for depletion of channel as shown in Fig. 3(d). Fig. 3(e) shows G_m-V_{GS} at V_{DS}=9 V of AlGaN/GaN DC-HEMT with InGaN. The InGaN layer makes higher carrier density. Moreover, InGaN exhibits high mobility. Their result is increased transconductance (G_m) of 165 mS/mm.

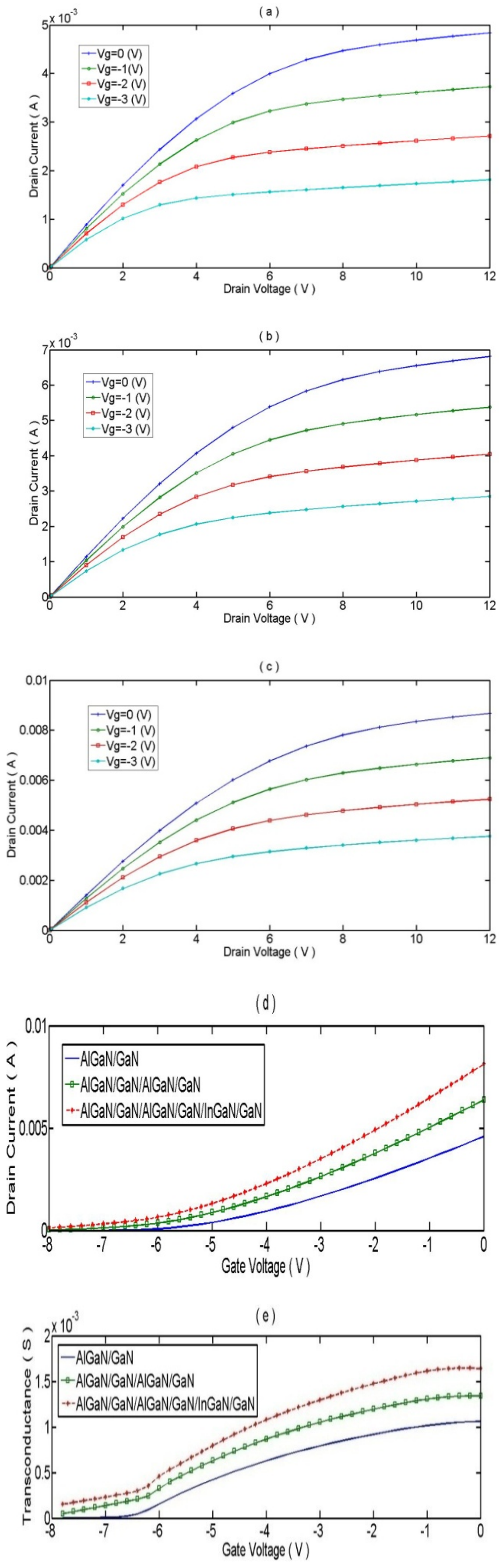


Fig.3. (a), (b) and (c) I_{DS}-V_{DS} for different gate voltage, (d) I_{DS}-V_{GS} for V_{DS}=9V, (e) gm-V_{GS} at V_{DS}=9V.

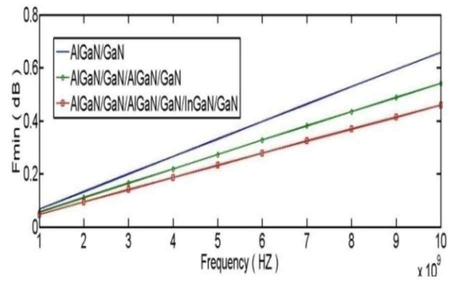


Fig.4. NF_{min}-F for V_{DS}=9V and V_{GS}=-0.2V.

4. Microwave Noise Characteristics

Fig. 4 shows minimum noise figure as a function of frequency for $Al_{0.3}Ga_{0.7}N$/GaN HEMT, AlGaN/GaN DC-HEMT and AlGaN/GaN DC-HEMT with InGaN biased at V_{DS}=9 V and V_{GS}=-0.2 V. Our simulations show that AlGaN/GaN DC-HEMT and AlGaN/GaN DC-HEMT with InGaN layer have lower noise than conventional AlGaN/GaN HEMT.

Generally, the minimum noise figure depends on the transconductance and gate-source capacitance

$(F_{min} = 1 + kfC_{gs}\sqrt{\frac{R_g + R_s}{g_m}})$, which F_{min} is the minimum

noise figure (dB), f, the frequency of operation (GHz), g_m, the transconductance (mS), Rg, the gate resistance function of device geometry (Ω), Rs, the source resistance function of device geometry (Ω), k, the fitting factor and will change with the device technology and bias, C_{gs}, the gate-source capacitance [14]. Since the gate-source capacitance of structures is nearly constant, the minimum noise figure is inversely proportional to transconductance [14]. The AlGaN/GaN DC-HEMT with InGaN layer shows a lower minimum noise figure (NF_{min}) of 0.046 dB at 1 GHz and NF_{min} of 0.45 dB at 10 GHz which is lower than that of AlGaN/GaN HEMT. This is because of higher transconductance than AlGaN/GaN HEMT.

The dependence of the noise performance of $Al_{0.3}Ga_{0.7}N$/GaN DC-HEMT with InGaN layer on gate bias was also simulated. Fig.5 (a) shows the dependence of the NF_{min} on the gate bias at 2 GHz with the drain voltage of 2 V. This figure has two sections, the gate voltage less than -4.2 V where the transistor is in its saturation region. With increase of the gate voltage, the number of carriers in the channel increases, as Fig. 5 (b) shows, the channel conductance increases, therefore the noise decreases. The second region in Fig. 5 (a) is for gate voltages above -4.2 V where the transistor is in its triode region. In this case with increase of the gate voltage the channel conductance decreases and therefore the noise increases. Fig. 5 (c) shows NF_{min} versus gate voltage at 2 GHz with the drain bias voltage of 10V. In this case the transistor is in its saturation region for the whole range of the gate voltages. Therefore with increasing the gate voltage, the conductance increases (Fig. 5 (d)) and as a result noise is decreased.

Fig. 6 (a) shows the dependence of NF_{min} of $Al_{0.3}Ga_{0.7}$ N/GaN DC-HEMT with InGaN layer on the drain voltage at 2 GHz and V_{gs}=-1.8 V. This figure also shows two regions. The region before V_{DS}=6 volts where the transistor is in its triode region. In this case with increasing the drain voltage noise decreases. As Fig. 6 (b) shows with increasing the drain voltage the channel conductance increases and as a result transistor noise is decreased. The second region in this figure is for drain voltages above 6 volts where the transistor is in its saturation region. In this case with increase of the drain voltage the noise is almost constant.

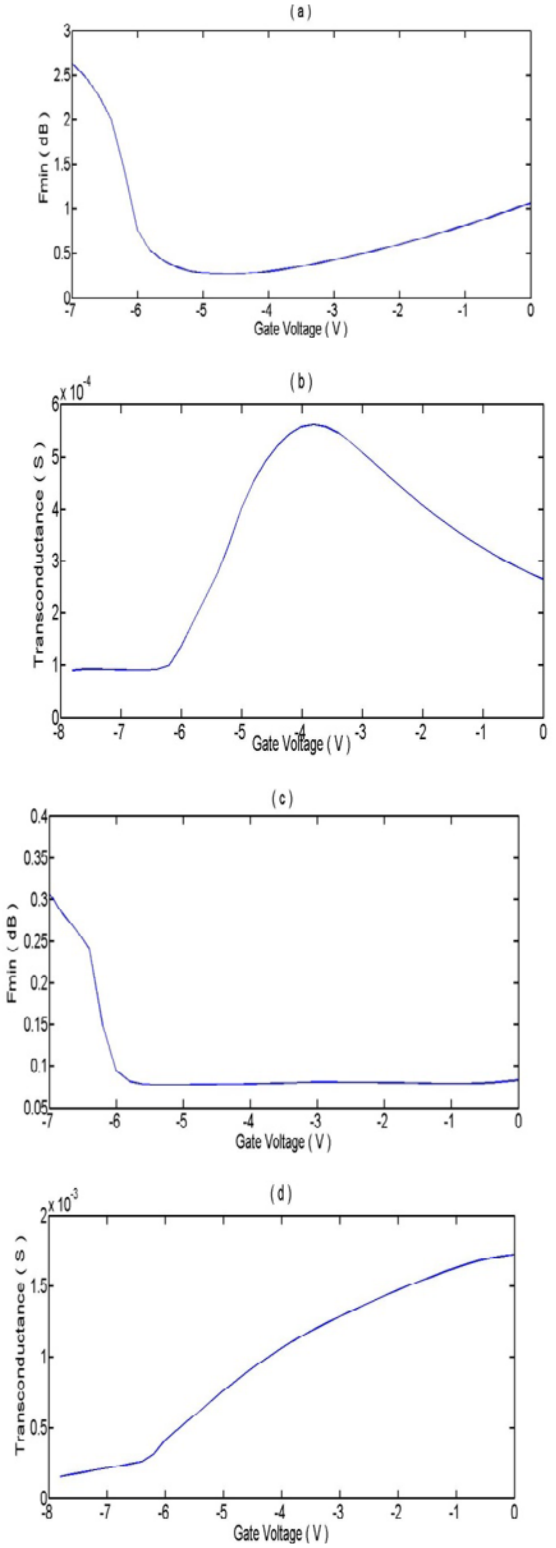


Fig.5. (a) NF_{min}-V_{GS} for V_{DS}=2 V and F=2 GHz, (b) G_m-V_{GS} at V_{DS}=2 V, (c) NF_{min}-V_{GS} for V_{DS}=10 V and F=2 GHz, (d) G_m-V_{GS} at V_{DS}=10 V.

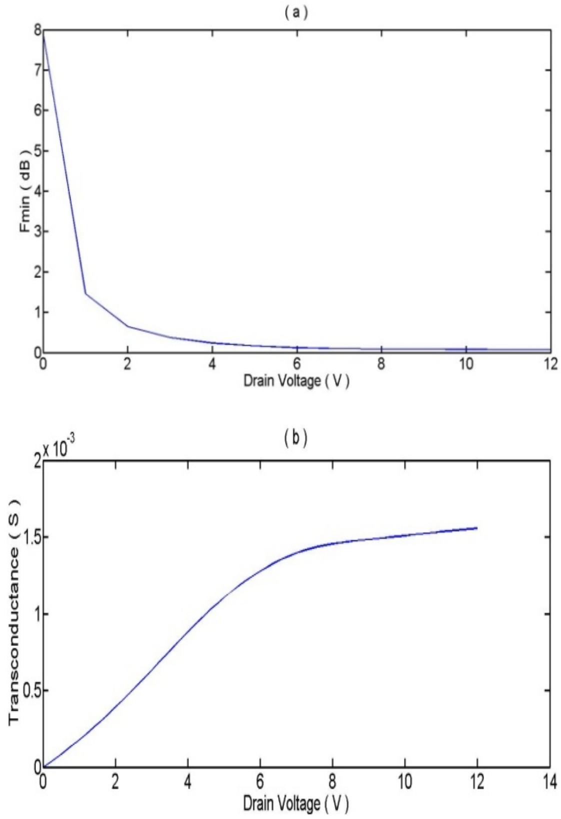


Fig.6. (a) NFmin-V_{DS} for V_{GS}=-1.8 V and F=2 GHz, (b) G_m-V_{DS} at V_{GS}=-1.8 V.

5. Conclusions

Detailed microwave noise characterizations simulation are carried out on $Al_{0.3}Ga_{0.7}N$/GaN HEMT, $Al_{0.3}Ga_{0.7}N$/GaN/$Al_{0.05}Ga_{0.95}N$/GaN DC-HEMT and $Al_{0.3}Ga_{0.7}N$/GaN/$Al_{0.05}Ga_{0.95}N$/GaN/$In_{0.1}Ga_{0.9}N$/GaN HEMT. The simulated noise of $Al_{0.3}Ga_{0.7}N$/GaN HEMT changes from 0.066 dB at frequency 1 GHz to 0.65 dB at frequency 10 GHz, 0.055 dB at frequency 1 GHz to 0.54 dB at frequency 10 GHz for DC-HEMT and 0.046 dB at frequency 1 GHz to 0.45 dB at frequency 10 GHz for DC-HEMT with InGaN layer Simulations show that DC-HEMT with InGaN has lower noise, better DC performance and larger transconductance than other structures. Also DC-HEMT shows lower noise and larger transconductance than conventional AlGaN/GaN HEMT. The noise characteristics of DC-HEMT with InGaN is investigated as a function of gate voltage as well as drain voltage and shown that with increase of transconductance noise decrease.

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