Investigation and Simulation of Double-gate Double-channel $In_{0.17}Al_{0.83}N$/GaN HEMT

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Abstract: In this paper a double-gate double-channel $In_{0.17}Al_{0.83}N$/GaN high-electron mobility transistors (HEMT) is proposed. This proposed structure compared with single-gate single-channel $In_{0.17}Al_{0.83}N$/GaN HEMT, and also this single gate structure is compared with $Al_{0.3}Ga_{0.7}N$/GaN HEMT. Simulation results confirm that proposed structure has higher drain current and transconductance.

Keyword: HEMT, Double-gate, Double-channel, transconductance.

I. Introduction:

Wide band gap GaN-based devices have been presented for the future high power and RF applications. The reason for this growing acceptance of AlGaN/GaN heterostructure as an alternative to Silicon-based power devices is attributed to the excellent material properties of III-Nitride semiconductors. In particular, the polarization-induced high-density high mobility sheet-type charge region, also known as 2-D electron gas (2-DEG) at the hetero-interface allows carrier transport with least scattering and loses thus, making AlGaN/GaN devices suitable for power electronics [1-3]. However, the AlGaN/GaN heterojunction structure suffers lattice defects due to lattice mismatch and piezoelectric effect, leading to reliability problems that have restricted the development of AlGaN/GaN heterojunction devices [4, 5]. Recently, InAIN/GaN appears as a new type III-nitride heterojunction structure. The $In_xAl_{1-x}N$ can be made lattice matched to GaN epilayer when the In composition of $In_xAl_{1-x}N$ is 0.17[6]. The lattice-matched $In_{0.17}Al_{0.83}N$/GaN high-electron mobility transistors (HEMTs), with the strong spontaneous polarization and strain-free barrier, are emerging as the promising candidate for high-frequency and high-power applications. Several work has done on $In_{0.17}Al_{0.83}N$/GaN HEMT [7-10].

II. Device Structure

In this section, investigated structures are defined and in the next section simulation results are represented and compared with each other.

The first structure is $Al_{0.3}Ga_{0.7}N$/GaN HEMT. This structure includes 24nm barrier layer of $Al_{0.3}Ga_{0.7}N$, 14nm GaN layer as a main channel, 2.5µm GaN layer as a buffer layer, and 2µm sapphire as a substrate. This structure has intrinsic barrier at the back of the channel to bound electrons, but owing to shortness of electron barrier in the channel, 2 dimensional electron gas (2DEG) is not formed well next to the buffer, and also, they drop to the buffer layer which results in high leakage current. On the other hand, owing to poor carrier bounding in the 2DEG channel, mobility reduces.

Second investigated structure is $In_{0.83}Al_{0.83}N$/GaN HEMT that is formed by replacing 15nm of $In_{0.17}Al_{0.83}N$ with 24nm of $Al_{0.3}Ga_{0.7}N$ barrier layer. $In_{0.17}Al_{0.83}N$ barrier layer compared with $Al_{0.3}Ga_{0.7}N$ barrier layer has larger band gap and polarization charges. In this structure, the thickness of barrier layer is 9nm less than first structure.

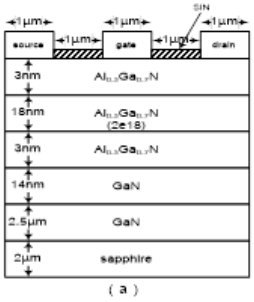
The third structure is a double-gate double-channel $In_{0.83}Al_{0.83}N$/GaN HEMT. This structure is formed by replacing 2.5µm GaN buffer layer and 2µm Sapphire substrate of single-gate single-channel $In_{0.83}Al_{0.83}N$/GaN HEMT with 15nm of barrier layer for bottom gate of double-gate structure. Gate control on channel in double-gate structure is higher than single-gate structure and simulation results confirm that current density and transconductance become 2 times more than single-gate structure.

III. Simulation Results

In this section, simulation results including DC and transconductance for all structures are shown.

A. $Al_{0.3}Ga_{0.7}N$/GaN HEMT

Fig. 1(Left) shows schematic of typical $Al_{0.3}Ga_{0.7}N$/GaN HEMT, and is based on [11]. In this structure gate length, source length, drain length and drain-gate distance is 1µm. The doping concentration of carrier supplier is 2e18. Lattice constant and band gap considered based on [12]. Fig. 1 (Right) shows conduction band of the $Al_{0.3}Ga_{0.7}N$/GaN HEMT, and as shown in the figure, the created potential well represents electron accumulation in that.



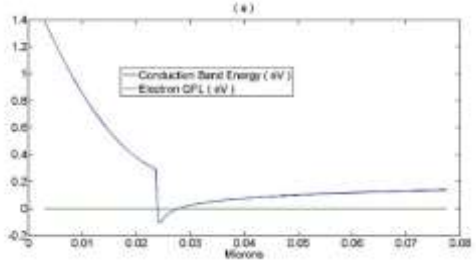


Fig. 1 (Left) schematic (Right) conduction band and Fermi level of $Al_{0.3}Ga_{0.7}N/GaN$ HEMT

The drain current characteristic with drain voltage for V_{GS}=0,-1,-2,-3(V) for $Al_{0.3}Ga_{0.7}N/GaN$ HEMT is shown in Fig. 2. For $V_D<V_G-V_T$ transistor operate in linear region, and for $V_D>V_G-V_T$ that works in saturation region.

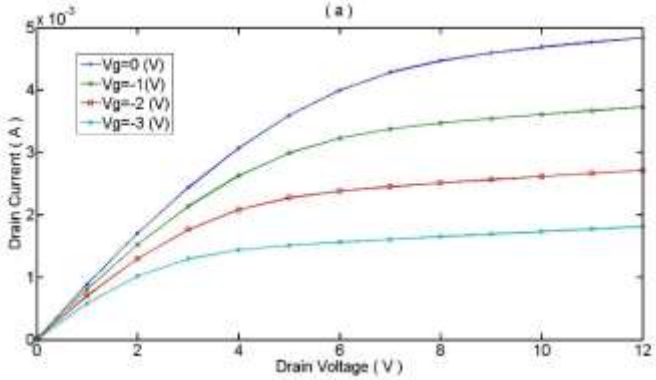


Fig. 2 I_D-V_{DS} for different V_{GS} of $Al_{0.3}Ga_{0.7}N/GaN$ HEMT

Fig 3(Left) shows drain current with gate voltage for V_{DS}=9(V), and as shown in this figure by increasing gate voltage, the drain current increases. As well as, In Fig. 3(Right) transconductance is shown with gate voltage for V_{DS}=9(V).

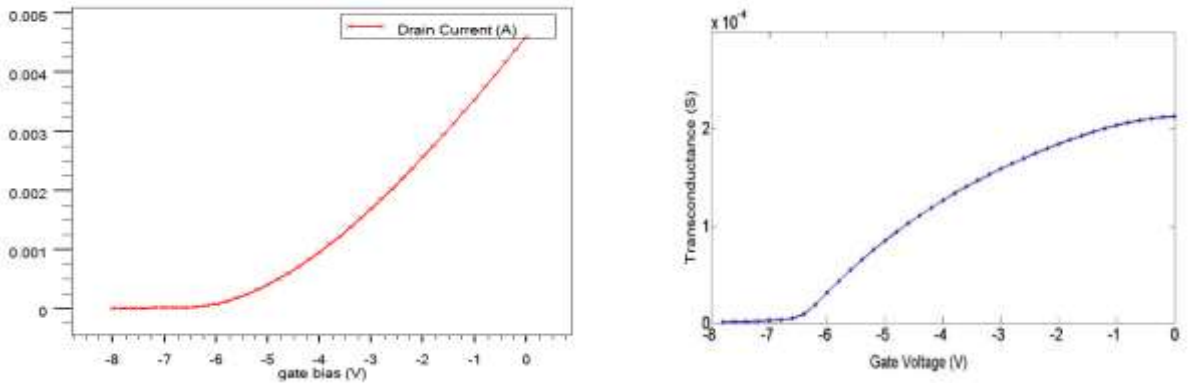


Fig. 3 (Left) I_D-V_{GS} (Right) transconductance-V_{GS} at V_D=9(V) of Al0.3Ga0.7N/GaN HEMT

B. $In_{0.17}Al_{0.83}N/GaN$ HEMT

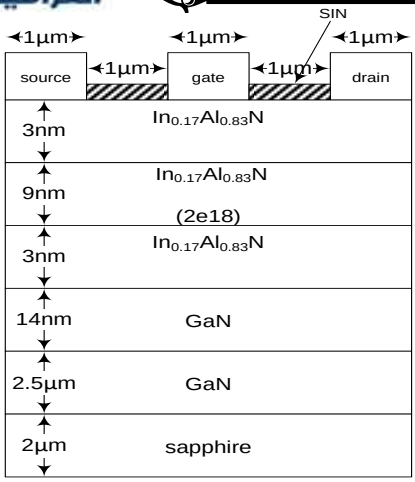
Next structure is $In_{0.17}Al_{0.83}N/GaN$ HEMT that is formed by replacing 15nm of $In_{0.17}Al_{0.83}N$ with 24nm of $Al_{0.3}Ga_{0.7}N$ of previous structure. Barrier layer of $In_{0.17}Al_{0.83}N$ has wider band gap and larger polarization charges than barrier layer of $Al_{0.3}Ga_{0.7}N$. In this structure the thickness of barrier layer is 9nm less than previous structure. Simulation results confirm that transconductance for this structure in higher than previous structure.

For $In_{0.17}Al_{0.83}N/GaN$ HEMT all structural parameters for simulation are based on $Al_{0.3}Ga_{0.7}N/GaN$ HEMT, and also the thickness of all layers are the same as previous structure. The only difference between them is that the 24nm of $Al_{0.3}Ga_{0.7}N$ barrier layer is replaced with 15nm $In_{0.17}Al_{0.83}N$ barrier layer. As well as, the thickness of spacer layer with cap layer is fixed and the thickness of supplier layer becomes half. Based on calculation in [12], $In_{0.17}Al_{0.83}N$ has wide band gap, and as a result polarization charge interface is higher than previous structure.

In this structure, the thickness of barrier layer is smaller than typical structure; therefore, gate control on channel in this structure is more than previous one. Owing to these reasons, this structure has higher current density and transconductance.

Fig. 4 (Left) shows schematic cross section of $In_{0.17}Al_{0.83}N/GaN$ HEMT, and Fig. 4 (Right) shows conduction band. Lattice constant and band gap of different layers of this structure, and also interface polarization charge of layers in $In_{0.17}Al_{0.83}N/GaN$ structure is based on[12].

As shown in Fig. 4 (Right), conduction band in interface of $In_{0.17}Al_{0.83}N/GaN$ goes under Fermi level, and it forms a channel which causes to bound carriers in GaN channel.



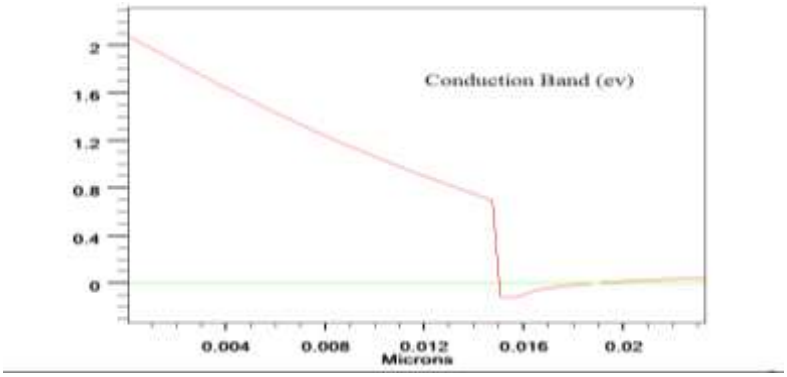


Fig. 4 (Left) schematic (Right) Conduction band and Fermi level of $Al_{0.3}Ga_{0.7}N$/GaN HEMT.

Fig. 5 shows drain current with drain voltage for 0,-1,-2 and -3(V) of gate voltages. As shown in the Fig. 5, in this structure, drain current in the same gate voltage is higher than that of $Al_{0.3}Ga_{N}$/GaN HEMT. Fig. 6 (Right) shows drain current with gate voltage for V_{DS}=9(V).

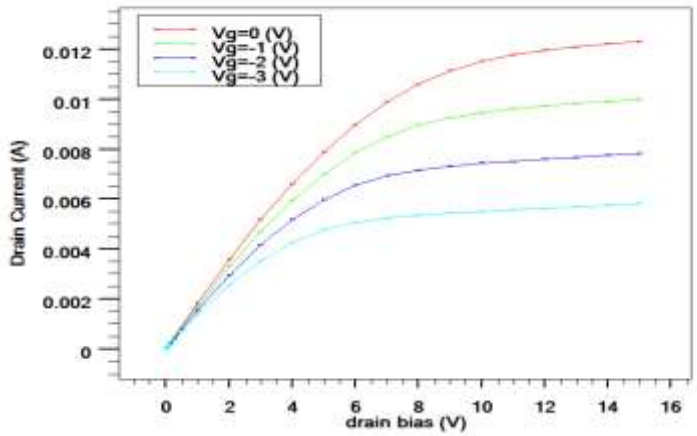
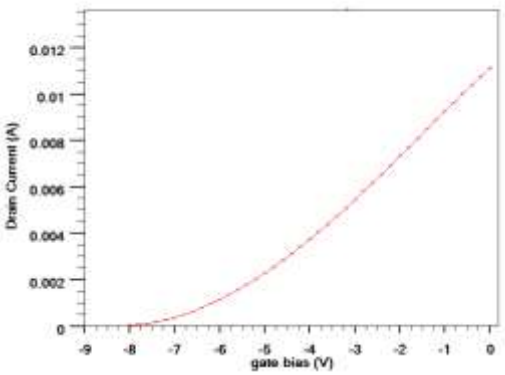


Fig. 5 I_D-V_{DS} for different V_{GS} of $In_{0.17}Al_{0.83}N$/GaN HEMT

Fig. 6 (Left) shows variation of transconductance with gate voltage for V_{DS}=9(V). By comparing the results of transconductance for $Al_{0.3}Ga_{0.7}N$/GaN HEMT and $In_{0.17}Al_{0.83}N$/GaN HEMT, it is concluded that transconductance of the structure with $In_{0.17}Al_{0.83}N$ barrier layer is higher than of the structure with $Al_{0.3}Ga_{0.7}N$.

In this structure, by increasing gate voltage, transconductance increases. By increasing gate voltage, carrier density in the channel increases. Therefore, the drain current and its variation increase. For higher gate voltage, transconductance saturates and has no change.



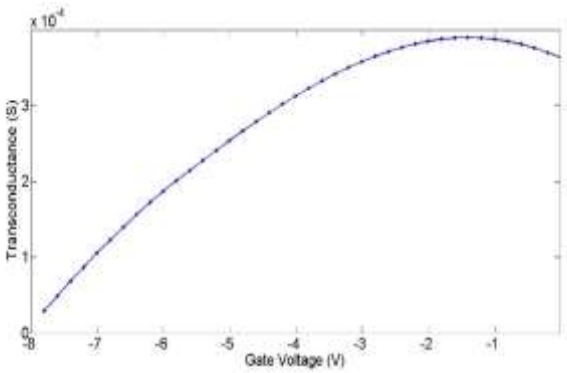


Fig. 6 (Left) I_D-V_{GS} (Right) transconductance-V_{GS} at V_D=9(V) of $In_{0.17}Al_{0.83}N$/GaN HEMT.

C. Double-gate $In_{0.17}Al_{0.83}N$/GaN HEMT

Last structure is a double-gate double-channel $In_{0.17}Al_{0.83}N$/GaN HEMT. In this structure, 2.5µm of GaN buffer layer and 2µm Sapphire substrate is replaced with 15nm barrier layer for bottom gate. In this structure,

gate control on the channel is high. Simulation results confirm that drain current for double-gate structure is 2 times higher than single-gate structure.

Fig. 7 (Left) shows schematic cross section of double-gate $In_{0.17}Al_{0.83}N$/GaN HEMT. Double-gate structure has smaller dimensions than typical structure because this structure does not have buffer layer and substrate. In this structure, 2.5µm of GaN buffer layer and 15nm of sapphire substrate are replaced with 15nm barrier layer is inserted at the bottom.

In double-gate double-channel structure, gate control on the channel is more than typical single-gate. In addition, current density and transconductance are about two times more than typical single-gate single-channel structure $In_{0.17}Al_{0.83}N$/GaN HEMT, and has smaller size, as well. Conduction band and Fermi level are shown in Fig. 7 (Right). In double-gate structure, conduction band goes under Fermi level.

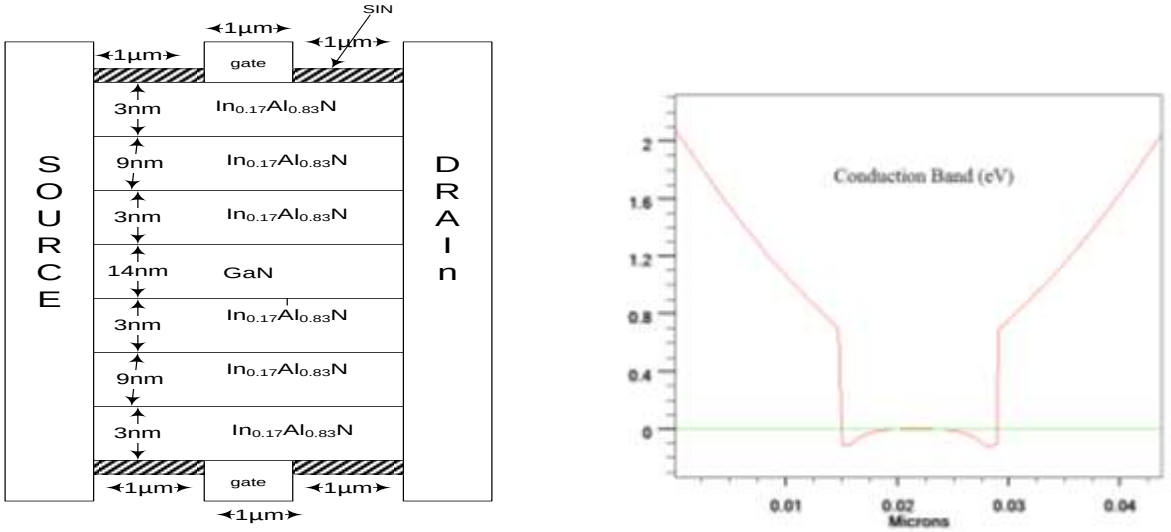


Fig. 7 (Left) schematic (Right) conduction band and Fermi level of double-gate $Al_{0.3}Ga_{0.7}N$/GaN HEMT.

Fig. 8 shows drain current with drain voltage at different gate voltages of 0,-1,-2, and -3(V). This structure has two times higher drain current than single-gate $In_{0.17}Al_{0.83}N$/ GaN HEMT. In this structure, gate-control on channel is more than single gate structure.

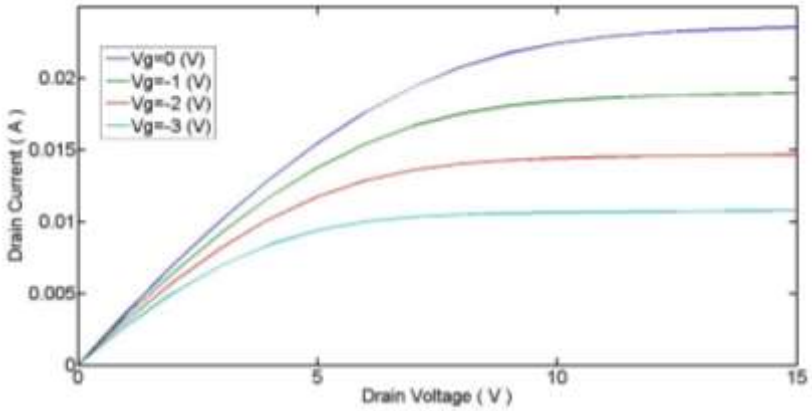


Fig. 8 I_D-V_{DS} at different V_{GS} of double-gate $In_{0.17}Al_{0.83}N$/GaN HEMT

Fig. 9 (Left) shows variation of drain current with gate voltage at V_D=9(V) for double gate $In_{0.17}Al_{0.83}N$/GaN HEMT. By increasing gate voltage and carrier density in channel, current increases, too. Fig. 9 (Right) shows variation of transconductance with gate voltage at V_D=9(V) for $In_{0.17}Al_{0.83}N$/ GaN HEMT. Transconductance is two times higher than single-gate structure.

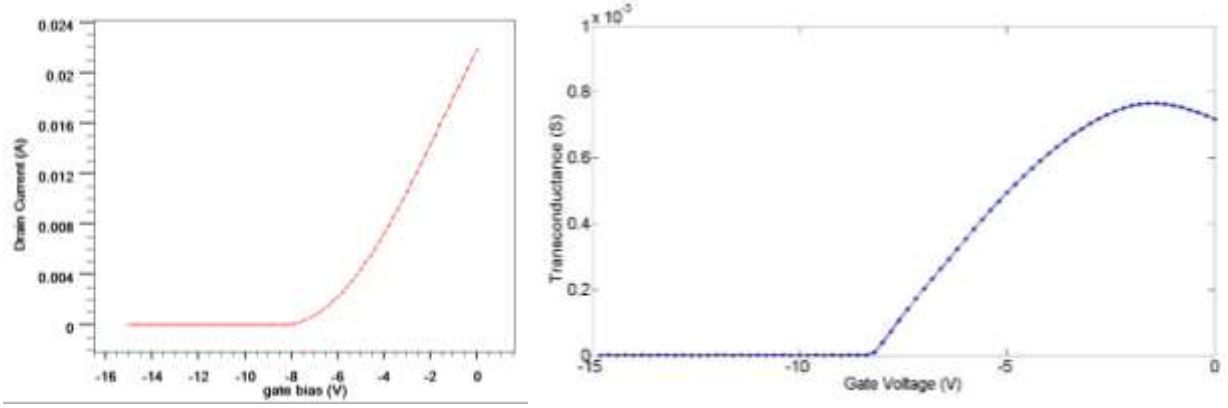


Fig. 9 (Left) I_D-V_{GS} (Right) transconductance-V_{GS} at V_D=9(V) of double gate $In_{0.17}Al_{0.83}N$/GaN HEMT.

IV. Result comparison

In this section, simulation results of double-gate double-channel and single-gate single-channel $In_{0.17}Al_{0.83}N$/GaN HEMT are compared. Fig. 10 shows drain current with gate voltage at V_D=15(V) for single-gate and double-gate $In_{0.17}Al_{0.83}N$/GaN. Simulation results show that at V_{GS}=0(V) and V_D=15(V) drain current are 120mA/mm and 240 mA/mm for single-gate and double-gate structures, respectively.

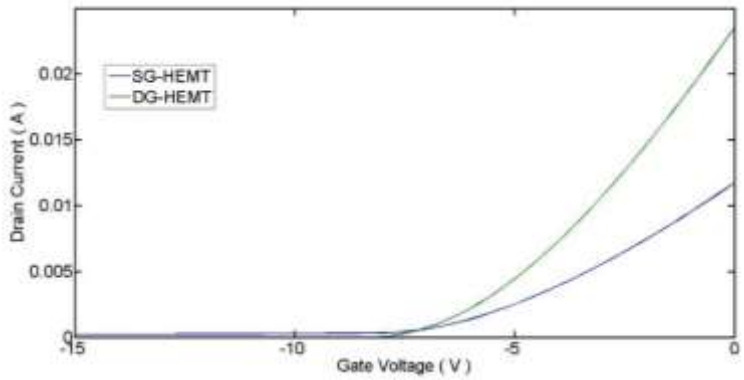


Fig. 10 I_D-V_{GS} of single-gate and double-gate $In_{0.17}Al_{0.83}N$/GaN HEMT

Fig. 11 shows variation of transconductance with V_{GS} at V_D=15(V) for single-gate and double-gate structures. At V_{GS}=0(V) and V_D=15(V), transconductance for single-gate and double-gate are 226mS/mm and 470mS/mm, respectively.

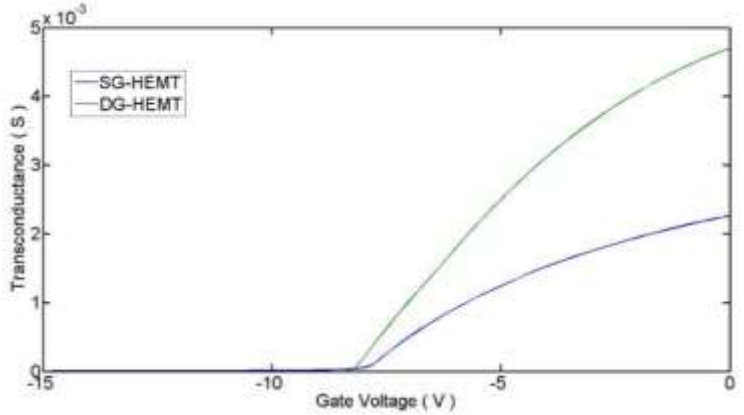


Fig. 11 Transconductance-V_{GS} of single-gate and double-gate $In_{0.17}Al_{0.83}N$/GaN HEMT

V. conclusion

AlGaN/GaN heterostructure considered as an alternative to Silicon-based power devices, but this material suffers from lattice mismatch. InAlN/GaN has appeared as a new type of III-nitride heterojunction structure for HEMT. As simulation results confirm that InAlN/GaN has better Dc and transconductance characteristic. In addition, if this structure uses as a double-gate double-channel structure, drain current and transconductance are enhanced. Simulation results show that at V_{GS}=0(V) and V_D=15(V) drain current are 120mA/mm and 240 mA/mm for single-gate and double-gate structures, respectively. As well as, transconductance for single-gate and double-gate are 226mS/mm and 470mS/mm, respectively.

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