Reduction of Current-Collapsing in Small Gate to Drain Length AlGaN/GaN Superjunction HEMT for High Frequency Application

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Abstract. In this work we analyzed a GaN-based super junction High Electron Mobility Transistor by Silvaco TCAD to improve the dc to ac conversion ratio and specific on-resistance for high frequency and high current but low voltage power devices. The gate to drain length of the device is reduced to augment the applicability of GaN HEMT at higher frequency. Additional base electrode increases the breakdown voltage of the device. Current collapsing is a detrimental effect in GaN HEMT which limits the maximum supply voltage. Aluminum mole fraction in undoped AlGaN layer is varied to reduce the current collapsing in the device.

Keywords: GaN-HEMT, Superjunction, Molefraction, Currant Collapse, Cut-off Frequency, Breakdown Voltage.

1 Introduction

GaN HEMT is well known and almost an ideal power electronic device for low ON-state resistance, high breakdown voltage, and high switching frequency [1-2] because of excellent physical properties such as wide energy band gap, high electron mobility, high electron saturation drift velocity, high critical electric field strength, the high thermal conductivity of GaN [3-5]. Additionally, Al-GaN/GaN heterointerface has two-dimensional electron gas (2DEG) with very high electron mobility. Owing to very high electron mobility AlGaN/GaN HEMT can make the system smaller and lighter, effectively making the inte-grated circuit more compact [6-7]. Thus it offers a huge market application prospect, especially in portable electronics products, such as mobile phones, laptops, MP3 players, PDAs, digital cameras, and other compact battery-powered products that have gained tremendous popularity in the marketplace during the last few years.

Though vertical GaN-FET offers a very high breakdown voltage (>1.2KV), lateral GaN-HEMT offers both low conduction losses due to the existence of 2-DEG and low switching losses because of lower parasitic capacitances[8]. There are a few techniques to improve the breakdown voltage [9-11]. Double heterojunction GaN/AlGaN/GaN structure offers both two-dimensional electron gas (2DEG) and two-dimensional holegas (2DHG) at GaN/AlGaN and AlGaN/GaN interface which flattens the electric field in the drift region which in turn increases the breakdown voltage. As far as the application voltage is limited to 500V lateral device is a better option in power applications [12]. One of the limitation of the AlGaN/GaN HEMT device is the drain current reduction with increasing drain bias in the saturation region of operation. This delimiting fact is known as current collapsing [13-14]. Several techniques hve been reported till date to manage the phenomena such as plasma passivation [15-17], field plates technique [14],[18], and current collapse may also suppressed by light illumination[19]

In this paper, we have studied the effect of the gate to drain length in terms of ON-current, ON-resistance, transconductance, cut-off frequency, and breakdown voltage by varying the mole fraction of Aluminum content in the undoped AlGaN layer from 0.25 down to 0.18 at channel length of 3 µm. The improvement of current collapsing with molar content Al in AlGaN is studied and analyzed in detail.

2 Device Structure and Simulation Scheme

The schematic structure of the simulated device is shown in Fig. 1. SILVACO ATLAS [20] is employed as the numerical device simulator, to simulate GaN-based super hetero junction High Electron Mobility Transistor (SHJHEMT). The structure starts with a 1 μm undoped GaN layer grown on a Sapphire substrate. We used an undoped GaN/AlGaN/GaN double heterojunction with a p-doped GaN cap layer. In addition to the source, the drain and gate electrode base electrode is incorporated just right into the gate electrode which makes a difference to the SHJHEMT from the conventional one. The base layer is formed on the 30 nm p-GaN cap layer and remains electrically shorted to the Schottky gate. The Schottky gate contact is formed by Ni/Au on the undoped 47 nm AlGaN layer. The thickness of the top undoped GaN layer is fixed to 10 nm. The work function of the gate stack is set to 5.1 eV. The length of the gate to drain is varied from 10 μm down to 1 μm. The doping concentration of the p-GaN cap layer is optimized for the maximally flat electric field in the drift region and set to 3×10^{19} cm^{-3}.
Ohmic and Schottky contacts are defined by setting the work functions of the metal. Poisson equation and continuity equations are solved self-consistently by incorporating physical models. Spontaneous polarization charges are included in the top and bottom interfaces of both GaN/AlGaN/GaN structures through the POLARIZATION model. The piezoelectric charge is calculated separately by the strain model using CALC.STRAIN is based on the lattice mismatch between AlGaN and GaN for different Al mole fractions in the AlGaN layer. Albrecht's (ALBRCT) mobility Model is used for the low field while the field-dependent Mobility Model (GANSAT) is used to account for the saturation of carrier velocity at high lateral fields. For the breakdown phenomena simulation, impact ionization is activated by the Selberherr (SELB) model. Physical parameters of AlGaN/GaN HEMT used in the simulation are shown in table no. 1.

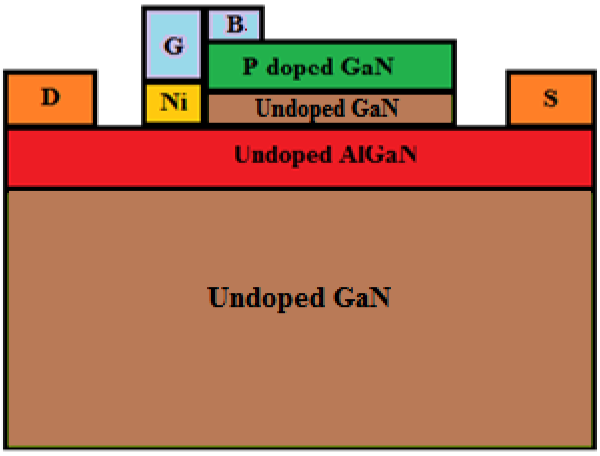

Fig. 1. Schematic diagram of super junction High Electron Mobility Transistor.

Table 1. Device parameter of AlGaN/GaN HEMT used in simulation.

Parameters	GaN	AlGaN
Saturation velocity(v_{sat}) (cm/s)	1.91×10^7	1.12×10^7
Electron mobility(μ_n) (cm^2/V.s)	1500	900
Relative permittivity(k)	8.9	8.8
Conduction band state density of states(N_c) (/cm^3)	2.24×10^{18}	2.74×10^{18}
Valance band state density of states (N_v) (/cm^3)	2.51×10^{19}	1.98×10^{19}
Energy bandgap (E_g) (eV)	3.43	3.87
Electron affinity (eV)	4.31	4.01

3 Calibration

The proposed device structure has been calibrated with the reported experimental results [21]. The output characteristics, shown in Fig. 2, from our simulation for the gate to drain length, L_{GD}=3μm at V_{DS}=10V of SHJHEMT show excellent matching with reported data that validates the models and model parameters used in our simulation.

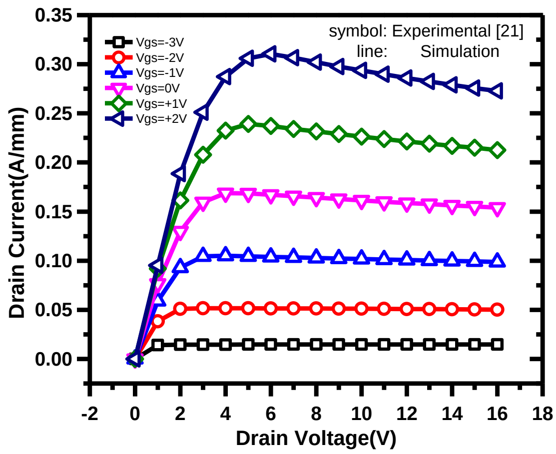

Fig. 2. Comparison of output characteristics obtained from TCAD simulation and reported experimental data at V_{DS} =10 V [21].

4 Results and Discussion

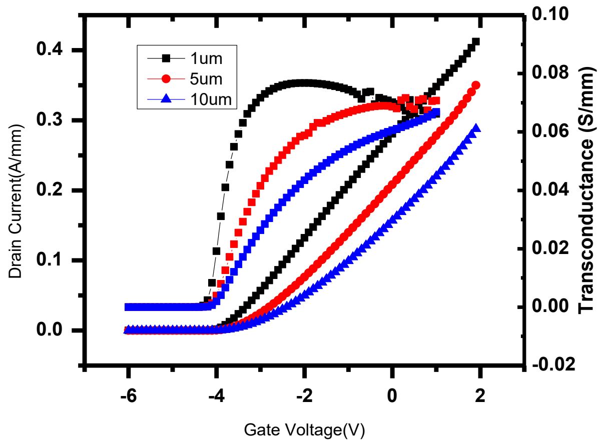

Fig. 3. Transfer characteristics of super junction HEMT with different gate to drain length (L_{GD}) at V_{DS}=10V.

Fig.3 shows the variation of drain current and transconductance with a gate voltage of the super junction HEMT for different values of the gate to drain length (L_{GD}) i.e 10µm,5µm, and 1µm at V_{DS}=10V. SHJHEMT offers the highest drain current for 1µm L_{GD} because of the small distance from the gate to the drain that increases the transit time of the electron which in turn raises the velocity towards the drain edge. The highest transconductance is also achieved for L_{GD}=1µm because of the higher sensitivity of drain current to the gate voltage. The maximum value of transconductance is obtained as 76.74 mS/mm at 1µm L_{GD}. The higher transconductance of the device enables higher dc to ac conversion efficiency.

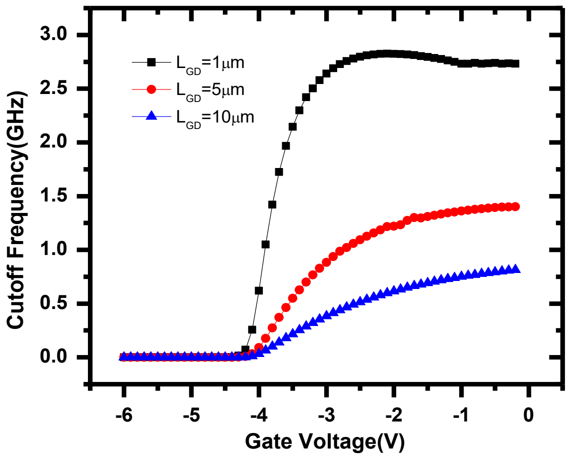

Fig.4. Cut off frequency super junction HEMT with different gate to drain length (L_{GD}) at V_{DS}=10V.

Fig.4 shows the variation of 3dB cut-off frequency with a gate voltage of super junction HEMT for various L_{GD}. The gate capacitance is extracted to calculate the cut-off frequency. A maximum cut-off frequency of 2.81 GHz is obtained for L_{GD} =1µm making the device suitable for 5G. Fig.5 shows the output characteristics of the super junction HEMT with different gate to drain lengths (L_{GD}) at V_{GS}= 2V. We have extracted ON-resistance from the linear region of the output characteristics and shown in table no. 2 along with ON current, maximum transconductance, and maximum cut-off frequency. The device having 1 µm L_{GD} shows excellent characteristics in terms of all parameters shown in table no. 2.

Table2. Different device parameter for different L_{GD}

L_{GD}(µm)	I_{ON}(A/mm)	R_{ON} (Ω.mm)	g_m (mS/mm)	f_{max} (GHz)
10	0.29	10.26	66.82	0.83
5	0.35	6.81	71.62	1.44
1	0.41	4.1	76.74	2.81

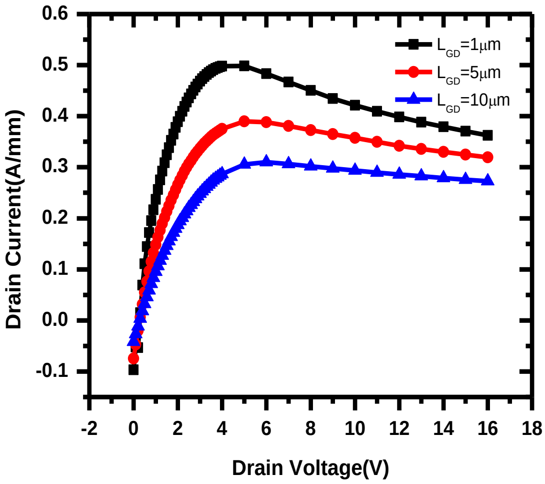

Fig.5. Output characteristics of super junction HEMT with different gate to drain length (L_{GD}).

An important concern in GaN HEMT is the current fall, known as current collapsing, at high values of V_{DS} as shown in Fig 5. As can be seen from the figure the current collapsing is more prominent in the 1 µm L_{GD} device.

Current collapsing occurs due to the trapping of hot electrons either near the surface of the AlGaN layer or at the AlGaN/GaN interface. The electric field becomes higher in the lower L_{GD} device and the depletion layer reaches the drain end resulting in hot electrons in the channel. Thus because of more hot electron trapping drain current collapses for the 1 µm L_{GD} device.

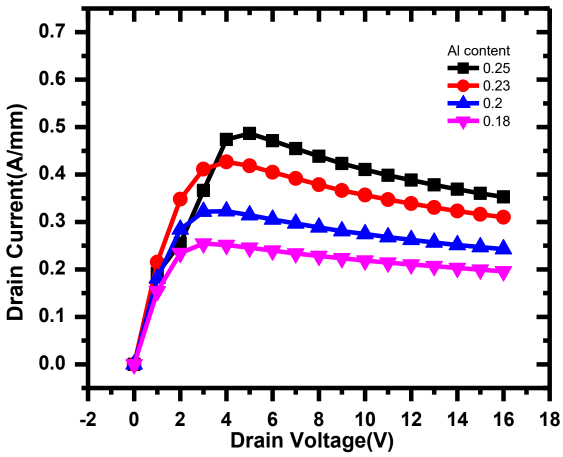

Fig.6. Output characteristics of super junction HEMT with different Al content in AlGaN at V_{GS}=1V and L_{GD} =1µm.

To keep the device away from the current collapsing we have varied the molar fraction of Al content in AlGaN from 0.25 to 0.18. It is clear from Fig. 6 that the drain current remains almost constant in the saturation region for 18% Al molar content in AlGaN.This is so because of the smaller bandgap of AlGaN for lower Al content. The smaller bandgap of AlGaN reduces the quantum well barrier which in turn reduces the electric field in the channel made by 2DEG in the quantum well formed at AlGaN/GaN interface. But at the same time ON current reduces significantly for 1 um L_{GD} device with 18% Al content. But the ON resistance remains almost constant over the mole fraction variation as shown in Fig.7.

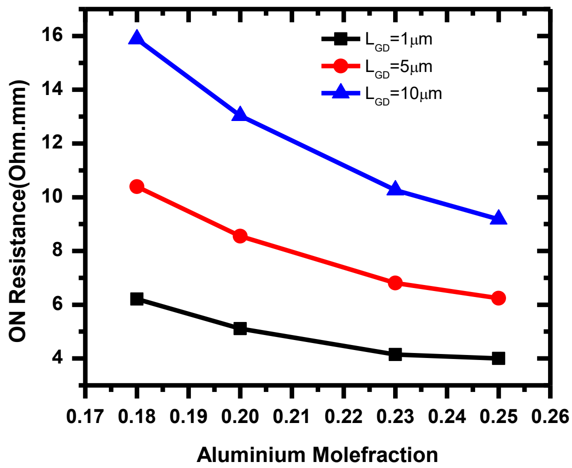

Fig.7. Comparison of ON resistance of super junction HEMT with different mole fraction of Aluminium in undoped AlGaN layer with different gate to drain length (L_{GD}) (10µm, 5µm and 1µm).

Additionally, we have achieved higher breakdown voltage for lower Al molar fraction as shown in table no.3. Thus the device can be operated safely below 100 V and is suitable for handheld battery-powered devices. Very high transconductance and cut-off frequency enable the device to be used for dc to ac conversion efficiently at a frequency as high as 2.9 GHz.

Thus we can create a design window for the 1µm L_{GD} SHJHEMT for different aluminum content as shown in table no.3.

Table3. Different design parameter for different Al molar content at L_{GD}=1µm

Al content	R_{ON}(Ω.mm)	g_m (mS/mm)	f_{max} (GHz)	Breakdown Voltage (V)
0.25	4.00	77.74	2.8	70
0.23	4.15	76.74	2.81	82
0.2	5.11	74.36	2.83	100
0.18	6.21	72.89	2.88	110

5 Conclusion

A super-junction AlGaN/GaN High Electron Mobility Transistor is studied with different gate-to-drain lengths (L_{GD}). The ON current is improved by 41.4% for L_{GD} of 1 µm SHJHEMT with respect to that of 10 µm SHJHEMT. ON-resistance and transconductance are improved by 59.5% and 25% respectively for L_{GD} of 1 µm SHJHEMT as compared to 10 µm SHJHEMT. Excellent improvement is observed in the Cut-off frequency of the 1 µm L_{GD} device which is 3.38 times larger than the 10 µm L_{GD} device. Current collapsing is brilliantly managed by reducing the mole fraction of the Aluminum in undoped AlGaN.

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