International journal of Engineering Research-Online
A Peer Reviewed International Journal
Articles available online http://www.ijoer.in

Vol.2., Issue.2., 2014

RESEARCH ARTICLE

ISSN:2321-7758

STUDY OF SIMPLIFIED THRESHOLD VOLTAGE OF ALGAN/GAN HEMT MODEL AND EFFECT OF CF_4 BASED PLASMA TREATMENT ON HEMT PERFORMANCE

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Article Received: 20/03/2014 | Article Revised on: 08/04/2014 | Article Accepted on:09/04/2014

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ABSTRACT

This paper presents impact of CF_4 plasma treatment on AlGaN/GaN high-electron mobility transistor (HEMT) parameters as threshold voltage, 2DEG density, drain current, trans conductance, drain trans conductance, and body trans conductance. Using CF_4 plasma treatment, the threshold voltage of AlGaN/GaN HEMTs can be continuously changed from −3.5 V in a conventional depletion-mode (D-mode) AlGaN/GaN HEMT to 0.4 V in an enhancement-mode (E-mode) AlGaN/GaN HEMT. The study results confirm that the threshold-voltage shift originates from the incorporation of F ions in the AlGaN barrier.

KEYWORDS---High Electron Mobility Transistor, CF_4 plasma treatment, threshold voltage, drain current, transconductance and 2DEG density

INTRODUCTION

The attention towards the study of III-V nitride based devices arise because AlGaN/GaN nitride based devices are best for High speed applications, high mobility, high peak saturation velocity and also for essential radiation hardness. The AlGaN/GaN HEMTs are considered mainly for power amplifiers in microwave products such as base stations. This work will investigate several performance enhancement parameters of GaN HEMTs. The plasma treatment improves the desirable device characteristics including transconductance, low on-resistance and low knee-voltage.

2. THEORETICAL MODEL OF THRESHOLD VOLTAGE

We have used a technique of fabricating high performance self-aligned E (enhance) mode AlGaN/GaN HEMTs using the fluoride-based plasma treatment. The control of the threshold voltage has been made through a modulation of energy band by F− ions implanted in the AlGaN/GaNheterostructure during the plasma treatment [1]. The fluorine ions have a strong electronegativity and are negatively charged, effectively raising the potential in the AlGaN barrier and the 2DEG channel. As a result, the V_{th} can be shifted to positive values. Taking into account the effects of charge polarization, surface and buffer traps, the threshold voltage of the AlGaN/GaN HEMT can be expressed as [2]

$$V_{th} = \frac{\emptyset_B}{e} - \frac{d\sigma}{\varepsilon} - \frac{\Delta E_C}{e} + \frac{E_{Fo}}{e} - \frac{e}{\sigma}\int_0^d dx \int_0^x N_{Si}(x)dx - \frac{edN_{St}}{\varepsilon} - \frac{eN_b}{C_b} \quad (1)$$

The last two terms in (1) describe the effects of the surface traps and buffer traps, respectively. The AlGaN surface is at $x = 0$, and the direction pointing to the channel is the positive direction for the integration. Now, let us consider a case, in which a certain amount of immobile negative charges is introduced into the AlGaN barrier layer under the gate (by plasma treatment). Because of electrostatic induction, these immobile negative charges can deplete 2DEG in the channel, raise the energy band, and hence modulate V_{th}. Including the effect of the negative charges confined in the AlGaN barrier, the modified threshold voltage from (1) is given by

$$V_{th} = \frac{\emptyset_B}{e} - \frac{d\sigma}{\varepsilon} - \frac{\Delta E_C}{e} + \frac{E_{Fo}}{e} - \frac{e}{\sigma}\int_0^d dx \int_0^x (N_{Si}(x) - N_F(x))dx - \frac{edN_{St}^{l}}{\varepsilon} - \frac{eN_b}{C_b} \quad (2)$$

Where all the parameters are summarized as

$\emptyset_B$ = metal-semiconductor Schottky barrier height., σ= overall net (both spontaneous and piezoelectric)polarization charge at the barrier AlGaN/GaNinterface, d = AlGaN barrier-layer thickness, E_{F0} = Difference between the intrinsic Fermi level and the conduction band edge of the GaN channel, ΔE_C = Conduction-band offset at the AlGaN/GaNheterojunction, $N_{Si}(x)$ = Si-doping concentration,N_F = Fluorine concentration, ε = Dielectric constant of AlGaN,N_{St} = Net-charged surface traps per unit area, N_b = Effective net-charged buffer traps per unit area,C_b = buffer capacitance.

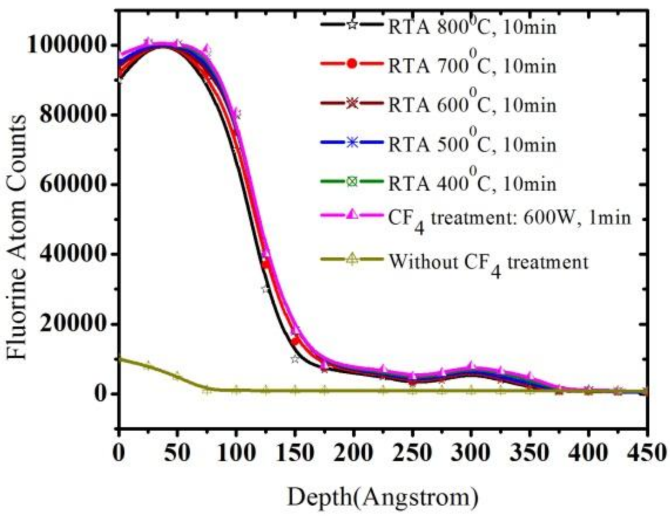

Figure 1: Fluorine atoms' distributions in AlGaN/GaN hetero structures treated by CF_4 plasma.

It was found that the fluorine ions, which were incorporated into the AlGaN barrier layer by CF_4 plasma treatment, could effectively shift the threshold voltage positively. The F− ions distribution in the AlGaN layer confirmed by secondary-ion-mass-spectrum (SIMS) measurements, as shown in Figure 1. SIMS measurement results shown in Figure 1 indicate that fluorine atoms count decreases as the depth increases. Now as we started the incorporation of plasma in the AlGaN layer with different plasma power and for various time duration. Then for increasing plasma power the fluorine atom counts is increased. For the conventional

HEMT, V_{th} is −3.5 V. For the HEMT treated by CF_4 plasma at 150 W for 150 s, V_{th} is 0.4 V, which corresponds to the E-mode HEMT. The higher is the plasma power and the longer is the treatment time, the larger is the shift in V_{th}.

2.1. CALCULATION OF 2- DIMENSIONAL ELECTRON GAS DENSITY OF HEMT

The density of the two- dimensional electron gas in a normal structure can be described using a charge control model [3,4]. We may write

$$n_s = \frac{\epsilon_N}{q(d+\Delta d)}(V_{GS} - V_{th}) \tag{3}$$

Where ϵ_N is the permittivity of the AlGaN, d is the thickness of AlGaN layer and Δd is the correction factor given by

$$\Delta d = \frac{\epsilon_N a}{q} = 80\text{Å} \tag{4}$$

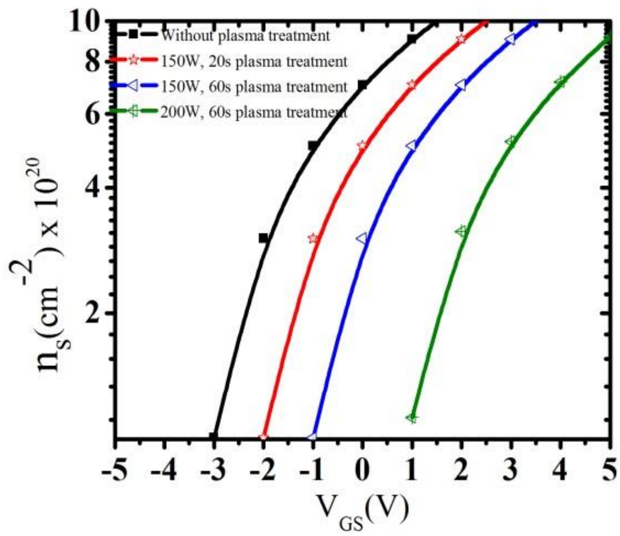

Figure 2: The simulated 2-DEG variation after treated by CF_4 (Fluoride-Based plasma)

The effect of fluorine based plasma on the two-dimensional electron gas density has been displayed in figure 2. The results show that after plasma treatment the density shifts toward the positive gate to source. The shift of the two-dimensional electron density depends upon the plasma rf (radio frequency) power and the plasma treatment power. The increasing the plasma power and plasma treatment time shift is increased more towards the positive gate to source voltage.

2.2. CALCULATION OF I-V (DRAIN CURRENT-VOLTAGE) OF HEMT

The drain current voltage characteristics of the high electron mobility transistor (HEMT) can be found the charge control model and gradual channel approximation [3]. The channel carrier concentration can be expressed as

$$n_s = \frac{\epsilon_N}{q(d+\Delta d)}[V_{GS} - V_{th} - V(x)] \tag{5}$$

Where V(x) is the potential along the channel due to the drain to source voltage. The drain current is

$$I_D = qn_s v(E) W \tag{6}$$

Where $v(E)$ is the carrier drift velocity and W is the channel width. Now assuming constant mobility, then for low V_{DS} values, we have

$$I_D = \frac{\epsilon_N \mu W}{2L(d+\Delta d)}[2V_{GS} - V_{th})V_{DS} - V_{DS}^2] \tag{7}$$

If V_{DS} increases so that the carriers reach the saturation velocity.The drain current curves in the figure 3 have been plotted after plasma treatment at different plasma power for various treatment time duration. The drain current curves shifted towards positive gate to source voltage after incorporation of plasma in the AlGaN layer. The incorporation of plasma shows the degradation in the drain current. But the degradation can be recovered by rapid thermal annealing (RTA).

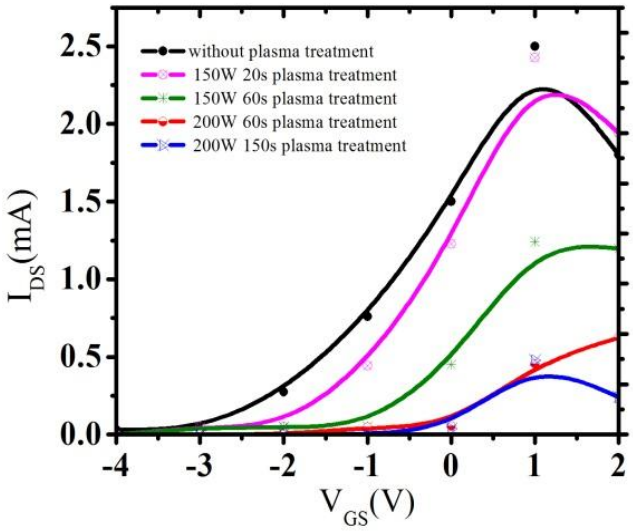

Figure 3: The simulated results of the drain current characteristics after treated by CF_4 (Fluoride-Based plasma)

2.3. CALCULATION OF TRAN CONDUCTANCE OF HEMT

The transconductance of high electron mobility transistor can be obtained by differentiating equation (7) w.r.t to V_{GS} as

$$g_m = \frac{\partial I_D}{\partial V_{GS}} \tag{8}$$

In the CF_4 plasma treated AlGaN/GaN HEMTs shown in figure 3 and figure 4 we observed drain–current and transconductance degradation just after the plasma treatment.

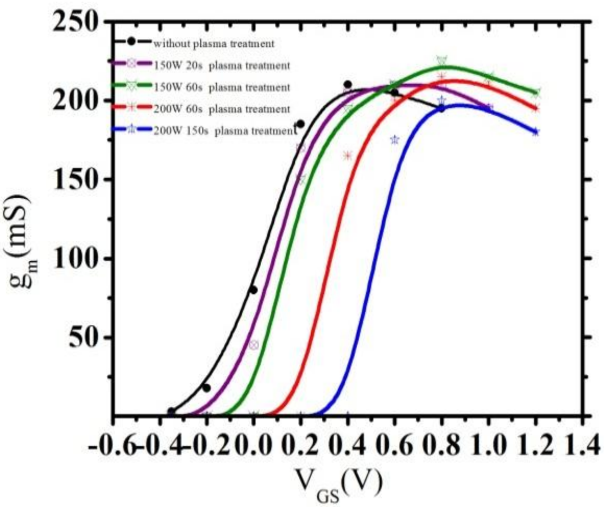

Figure 4: The simulated results of the transconductance after treated by CF_4 (Fluoride-Based plasma)

The devices with 200 W and 150 s fluorine plasma treatment exhibit small output current and small transconductance, which can be attributed to the implantation of a F ion in the channel. As the plasma normally induces damages and creates defects in semiconductor materials, and consequently degrades carriers' mobility so RTA (rapid thermal annealing) is an effective method to repair these damages and recover the mobility [4-6].

2.4. CALCULATION OF DRAIN TRANS CONDUCTANCE OF HEMT

The transconductance of high electron mobility transistor can be obtained by differentiating equation (7) w.r.t to V_{DS} as

$$g_{DS} = \frac{\partial I_D}{\partial V_{DS}} \quad (9)$$

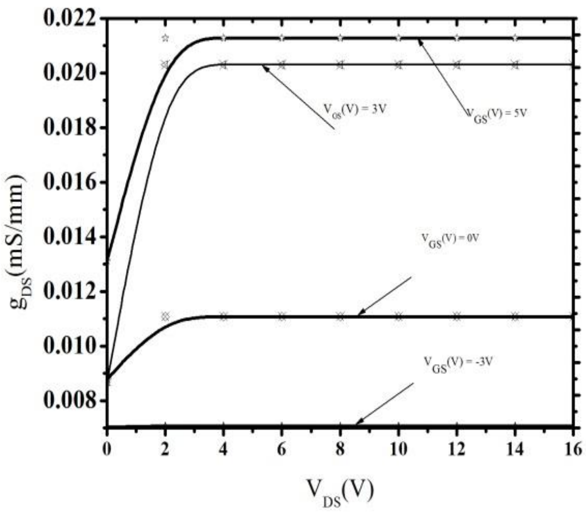

Figure 5: The simulated results of the drain trans conductance characteristics at -3.5V threshold voltage [without CF_4 (Fluoride-Based plasma) treatment]

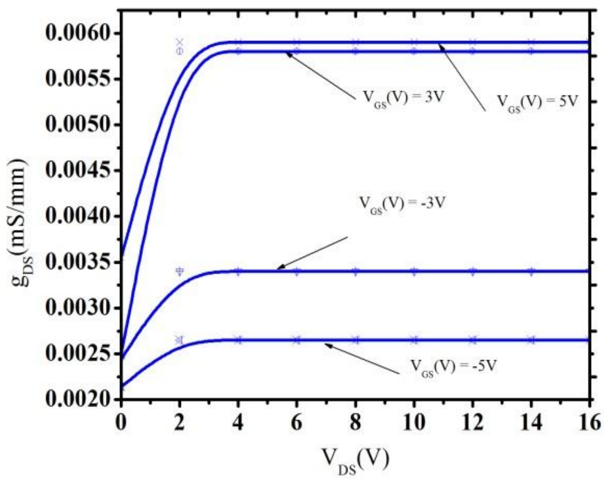

Figure 6: The simulated results of the drain trans conductance characteristics at 0.4V threshold voltage [after CF_4 (Fluoride-Based plasma) treatment]

In the CF_4 plasma treated AlGaN/GaN HEMTs shown in figure 5 and figure 6 it has been observed that the drain trans conductance degraded just after the plasma treatment.

2.5. CALCULATION OF BODY TRANS CONDUCTANCE OF HEMT

The body effect may occur in HEMT devices when the source is not tied to the substrate (which is always connected to the most negative power supply) is characterized by body trans conductance, defined as

$$g_{mb} = \chi g_m \tag{10}$$

$$\chi = \frac{\partial V_{th}}{\partial V_{SB}} = \frac{\gamma}{2\sqrt{2\phi_f + V_{SB}}} \tag{11}$$

Where χ is parameter which has value in the range of 0.1 to 0.3, V_{SB} is the source to body voltage and ϕ_f is work function

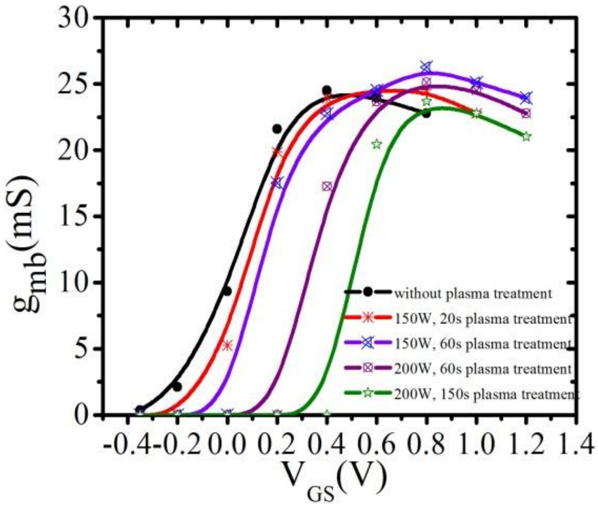

Figure 7: The simulated results of the body trans conductance characteristics with CF_4 (Fluoride-Based plasma) treatment

The reduction in body trans conduction indicates that the plasma treatment reduces body effect.

2.6. CALCULATION OF ON RESISTANCE OF HEMT

The on resistance is an important parameter of power high electron mobility transistor, which can be written as

$$R_{ON} = R_S + R_{CH} + R_D \tag{12}$$

Where R_S is the resistance associated with the source contact, R_{CH} is the channel resistance and R_D is the resistance associated with the drain contact. In the linear region of operation, we may write the channel resistance as

$$R_{ON} = R_S + R_D + \frac{L}{W\mu_n C_{ox}(V_{GS} - V_T)} \tag{13}$$

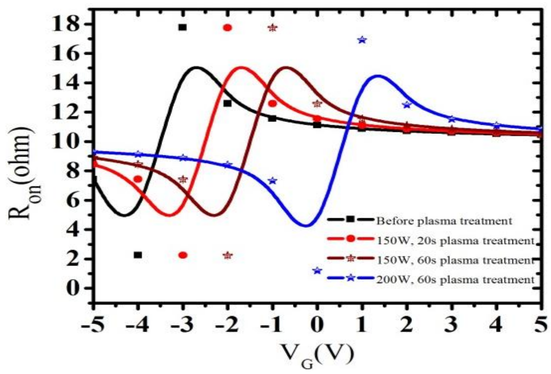

Figure 8: The simulated results of the on resistance characteristics of high electron transistor

The on resistance decreases as plasma treatment time and plasma power which reduces the power dissipation. By increasing plasma power and plasma treatment time the on resistance is changed a little and shifted towards positive gate to source voltage.

3. CONCLUSION

A innovative approach based on CF_4 based plasma treatment has been demonstrated to fabricate E-mode AlGaN/GaN HEMTs. The plasma treatment can effectively implant negatively charged fluorine ions into the AlGaN barrier and positively shift the threshold voltage, The fabricated E-mode AlGaN/GaN HEMTs showed a $V_{th}$of 0.4 V. Thus we are able to fabricate high-performance E-mode HEMTs with low on-resistance and low knee voltages, low power dissipation which are required for single-polarity supply voltage amplifiers and integrated digital circuits.

ACKNOWLEDGMENT

Authors would like to thank ISM DHANBAD for their support.

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