SHEET CARRIER CHARGE IMPROVEMENT OF ALGAN/GAN HEMT USING 2DEG COMPARED WITH 2DHG BY MITIGATION LOSS OF DRAIN POTENTIAL

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Abstract

Aim: An accurate charge control model is proposed with the 2DHG to look over the effect of doping, strain relaxation, aluminum composition, and thickness of the AlGaN/GaN barrier layer on the piezoelectric with continuous polarization induced 2-DEG sheet charge density and output characteristics of the temporarily relaxed AlGaN/GaN HEMT (2DHG).

Materials and methods: In the closed gate AlGaN/GaN HEMT, the controlled 2DEG is going to succeed a great performance in power electronic devices by adding the parameter of recess high. Two groups are considered where, group 1 is 2DEG and group 2 is 2DHG. Each group has 7 samples and a total of 14 sample sizes.

Results: The charge density of 2DEG gets increased in channel, when the mole fraction of Al gets increasing for an experiment of open gate AlGaN/GaN HEMT. SPSS analysis is carried out and has a significance of 0.0098 ($p<0.05$, statistically significant).

Conclusion: The two dimensional electron gas (2DEG) provides better improvement of sheet carrier density compared to two dimensional hole gas (2DEG).

Keywords: Two-dimensional electron gas (2DEG), Two-dimensional hole gas (2DHG), High electron mobility transistors (HEMT), Sheet carrier charge density, Polarization, Novel device AI optimization, Power electronics.

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1. Introduction

The AlGaN/GaN HEMT has displayed its great potential for use in the high gain of power, high range frequency, wide direct bandgap and increased thermal stability (Godfrey et al. 2020). High electron mobility transistor (HEMT) is an optimistic candidate for our current digital communication system for power electronics, because its switching speed is high and it consumed less power (Prasad, Dwivedi, and Islam 2016). The HEMT are now being used in the applications of high gain of frequency as well as high gain of power such as radar, imaging, radio astronomy and also used in microwave range and millimeter wave range communication (Mohapatra and Dutta 2020)(Sharbati et al. 2021)(Mohapatra and Dutta 2020).

Recently, a lot of research has been done related to the sheet carrier density of AlGaN/GaN HEMT and about 72 articles have been published in google scholar. An accurate in charge control model for spontaneous as well as piezoelectric polarization dependent 2DEG sheet charge density of lattice which is not matched having AlGaN/GaN HEMTs (Rashmi et al. 2002). Based on physics, an analytical model of 2DEG charge density in AlGaN/GaN HEMT devices (Khandelwal, Goyal, and Fjeldly 2011). Modeling of 2DEG and also 2DHG in i-GaN capped based AlGaN/AlN/GaN HEMTs (Faramehr, Kalna, and Igic 2014). Analytical model for 2DEG of charge density of recessed-gate GaN based HEMT (Sharbati et al. 2021).

Our institution is passionate about high quality evidence based research and has excelled in various domains (Vickram et al. 2022; Bharathiraja et al. 2022; Kale et al. 2022; Sumathy et al. 2022; Thanigaivel et al. 2022; Ram et al. 2022; Jothi et al. 2022; Anupong et al. 2022; Yaashikaa, Keerthana Devi, and Senthil Kumar 2022; Palanisamy et al. 2022).The work involves analyzing the sheet carrier charge density improvement by drain voltage variation in AlGaN/GaN HEMT by using Novel device AI optimization. This proposed work explores the improvement of sheet carrier charge density by varying the drain voltage using 2DEG and 2DHG.

2. Materials and Methods

The study was followed through the Power Electronics laboratory, Department of Electrical and Electronics Engineering, Saveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences. Two algorithms have been compared and by using GPower software, their sample size has been obtained and it is determined that each algorithm has 7 samples and a total 14 sample tests have been taken (EL-Sayed 2017). The incorporated Gpower parameter value is 0.80, and max error which got fixed is 0.5, mean group values $2.1716*10^{17}$ and $2.162*10^{17}$ and standard deviation values $8.0881e^{17}$ and $8.14729e^{17}$. The proposed research work is simulated using the matlab (R2013a) software.

Two Dimensional Electron Gas (2DEG)

For the purpose of reliable model HEMT, an accurate evaluation of 2DEG density in heterointerface which has significant importance (Mohapatra and Dutta 2020). The sheet carrier density of 2DEG is induced in slightly undoped AlGaN/GaN HEMT heterostructure by effects of polarization (Javorka 2004). The heterostructures with the AlGaN on head of GaN are under tensile strength, thus the addition of spontaneous polarization fields and piezoelectric which gives total polarization (Prasad, Dwivedi, and Islam 2016). The gradient in the polarization between AlGaN/GaN interface free electrons tends to be collected at interfacing thus forming a conductive channel (Ma et al. 2015).

From the proposed model for the sheet carrier charge density improvement of two-dimensional electron gas (2DEG) for high electron mobility transistors (HEMT) is done by varying the drain voltage. Based on the given inputs in the program the output has been obtained. Those inputs are $q=1.6*10^{-19}$,$c_g=6.8653*10^{-3}$, $c_{g1}=6.884615*10^{-3}$, $c_{g2}=6.83*10^{-3}$, eps_chp=$9.755e^{-12}$, v_t=-5.45, $g=2.12*10^{-12}$.

Two-Dimensional Hole Gas (2DHG)

In HEMT, the 2DHG is formed on the head of GaN/AlGaN interface in which polarization charge is negative is combined with 2DEG which is formed on bottom of GaN/AlGaN interface in which the polarization charge is negative comes under certain parameter condition like barrier thickness, potential and cap (Reuters et al. 2014). The relatively thick GaN cap creates non-negligible influences in the 2DEG. To define the impact of 2DEG with obtained density n_s and SBH, the effect of conduction band (CB) is joined with the valence band (VB) (Douglas et al. 2019). The incidence of 2DHG confines the carrier charge of 2DEG interior of quantum well (QW) by using novel device AI optimization methods that leads to the dynamic performance improvement of the device (Hahn et al. 2015).

From the advanced model for the sheet carrier charge density improvement of 2DHG using HEMT is done based on varying the drain voltage. Based on the given inputs in the program the output has been obtained. Those inputs are $q=1.6*10^{-19}$,$c_g=6.8653*10^{-3}$, $c_{g1}=6.884615*10^{-3}$, $c_{g2}=6.83*10^{-}$

^{3}, eps_chp=9.755e^{-12}, d_chp=33e-9, phi_Bp=1.34, v_{t1}=-4.8.

Charge Density in 2DHG and 2DEG

A heterostructure AlGaN/GaN HEMT having charge densities p_s and n_s which is derived and its effect on the performance of the device were discussed in this project (N., N., and A. 2019).

Charge density in 2DHG

The 2DHG is used to derive the equations by using gauss law which is interfaced at each layer and on the outside of heterostructure, the zero fields are recognized.

$$p_s = \frac{1}{e}\left[\frac{\sigma_b - \sigma_{ch,p} - C_{ch,p}\left(1+\frac{C_b}{C_{ch,n}}\right)\emptyset_{B,p} + \frac{C_b}{C_{ch,n}}\sigma_n - C_b\emptyset_p}{1 + C_b\frac{\pi h^2}{em^*} + \frac{C_b}{C_{ch,n}}}\right] \quad (1)$$

Where σ_b, $\sigma_{ch,p}$, and $\sigma_{ch,n}$ = the whole polarization charges of lower and upper barrier material AlGaN (equally sizes of two latter), σ_n = electron charge density, σ_p = hole charge density, $\varepsilon_{ch,p}$ = p-channel specific permittivity, $\varepsilon_{ch,n}$ = n-channel specific permittivity, $\in_{ch,p}$ = p-channel electric field, $\in_{ch,n}$ = n-channel electric field, $C_{ch,p}$ = p-channel thickness, $C_{ch,n}$ = n-channel thickness and C_b = barrier thickness. The equation (1) is helping to find the two dimensional hole gas (2DHG) in the HEMT.

Sheet Carrier Density I region

By preferring V_d other than nearby voltage to cutoff, E_f is going much lesser compared to V_{go}. In region 1 and region 2, sheet density of n_s is developed independently. Both region based carriers are incorporated, thus the model of the device is developed.

The sheet carrier density n_s of developed model HEMT in region 1 is given below

$$n_s^I = \frac{C_g v_{go}}{e}\left[\frac{1-\gamma_0\left(\frac{C_g v_{go}}{e}\right)^{\frac{2}{3}} + V_{th}\ln\beta v_{go}}{v_{go} + v_{th} + 2/3\gamma_0\left(\frac{C_g v_{go}}{e}\right)^{\frac{2}{3}}}\right] \quad (2)$$

Where C_g= gate capacitance.

The equation (2) which represents n_s of region 1 to the subband level of ground state energy.

Sheet Carrier Density II region

The relationship equation for n_s of second region is placed below

$$\frac{n_s^{II}}{D} + E_0 = E_F^{II} \quad (3)$$

The final expression of region 2 n_s which is given by

$$n_s^{II} = \frac{C_g v_{go}\left[v_{go} - \frac{\gamma_0}{3}\left(\frac{C_g v_{go}}{e}\right)^{\frac{2}{3}}\right]}{e\left[v_{go}(1+\beta v_{th}) + \frac{2}{3}\gamma_0\left(\frac{C_g v_{go}}{e}\right)^{\frac{2}{3}}\right]} \quad (4)$$

The equation (3) and (4) employs the determination of n_s in QW with the subbands of e_0 and e_1 incorporating functions such as region 1 and region 2 sheet carrier density. These two regions help in finding I_d and V_d of 2DEG and 2DHG.

3. Results

The work gives the insight of the relationship between 2DEG and 2DHG of AlGaN/GaN HEMT for the improvement of n_s. The 2DEG density increases with a rise of mole fraction in Al for the AlGaN barrier layer because the conduction band discontinuity gets increased and impulsive piezoelectric polarization fields occur in the AlGaN interface.

Table 1 shows the total number of 14 samples for group 1 and group 2 with 7 samples each, the samples are sheet carrier charge density in percentage. Group 1 is 2DEG and group 2 is 2DHG.

Table 2 represents the T-test comparison of 2DEG and 2DHG for mean value, standard deviation value, and the standard error of sheet carrier charge density. The standard error mean value for 2DEG is 3.05704e^{17} and for 2DHG is 3.07939e^{17} which ensures the proposed method's superiority.

Table 3 represents the Independent samples of test for standard error determination and significance with 2DEG and 2DHG. Significance value obtained as 0.0098 ($p<0.05$), considered to be statistically significant with a 95% confidence interval.

Figure 1 shows the comparison of 2DEG with respect to V_{gs}. From the equation (2-4), the max of electron sheet charge density is about 3.29481e^{17} at 5V source to gate voltage.

Figure 2 shows the comparison of 2DHG in accordance with the V_{gs}. From the equation (1), the max of hole sheet charge density is about 3.29413e^{17}at 5V source to gate voltage.

Figure 3 shows the difference of sheet carrier charge density regarding the V_{gs} based on HEMT). The maximum sheet charge density of 1.72e^{16} is obtained at 4V source to gate voltage.

Figure 4 depicts the bar graph analysis on sheet carrier charge density of both 2DEG and 2DHG. It is inferred that 2DEG produces better sheet carrier charge density improvement compared to the 2DHG.

4. Discussions

The sheet carrier charge density improvement of HEMT is discussed with the 2DEG and 2DHG. When compared to a conventional method, the proposed method is more efficient.

An accurate charge control model for spontaneous and piezoelectric on polarization dependent 2DEG sheet charge density ($2.94e^{17}cm^{-3}$) of lattice which get mismatched by AlGaN/GaN HEMT (Rashmi et al. 2002). A physics dependent analytical model of 2DEG charge density in AlGaN/GaN HEMT of power devices of ($3.29e^{17}cm^{-3}$) (Khandelwal, Goyal, and Fjeldly 2011). Modeling of 2DHG and 2DEG in HEMT of capped i-GaNs produces sheet density of ($2.54e^{17}cm^{-3}$) (Faramehr, Kalna, and Igic 2014). Analytical model for 2 DEG charge density ($3.66e^{17}cm^{-3}$) in recessed- gate GaN in HEMT (Sharbati et al. 2021). These papers are encouraging the improvement of the sheet carrier charge density by varying the drain voltage of the HEMT.

Some of the opposing papers are also there in the high electron mobility transistor for the improvement of sheet carrier charge density. Charge balancing in GaN-based 2-D electron gas devices employing an additional 2-D hole gas and its influence on dynamic behavior of GaN-based heterostructure field effect transistors having ($0.67e^{17}cm^{-3}$) of sheet density (Hahn et al. 2015). Analysis of 2-DEG characteristics in GaN HEMT with AlN/GaN superlattice as barrier layer grown by MOCVD have sheet density of ($0.43e^{17}cm^{-3}$) (Xu et al. 2012).

Decrease in n_s which is based on the reduction of barrier thickness, so the polarization charge point gets decreased. Hence the mole fraction of Al which gives rise to the barrier layer of AlGaN HEMT because discontinuity of conduction band is increased. By changing V_{gs} in accordance with n_s display its excellent agreement.

The HEMT are rapidly transpiring because they demonstrate as a bright device for widespread applications in ICs with elevated speed, because its power consumption is less, fabrication is simple and it has a tremendous switching speed.

5. Conclusion

In this work, sheet carrier charge density analysis was carried out in both 2DEG and 2DHG. From the result obtained, we can see that the 2DEG has a sheet carrier density improvement of $3.96e^{17}cm^{-3}$ and two dimensional hole gas has a sheet carrier density improvement of $3.29cm^{-3}$. So we conclude that the two-dimensional electron has a better improvement of charge density in AlGaN/GaN HEMT. Based on SPSS analysis the significance value is 0.0098 ($p<0.05$) which is considered to be statistically significant.

Declarations

Conflict of Interests

No conflict of Interest in this Manuscript

Author contributions

Author MD was involved in data collection, data analysis, and manuscript writing. Author AN was involved in data validation and review of manuscripts.

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Tables and Figures

Table 1. Simulated result of the simulated two-dimensional electron gas (2DEG) and two-dimensional hole gas (2DHG) algorithm for AlGaN high electron mobility transistors (HEMT) for the improvement of sheet carrier charge density.

Sl.No	Drain Voltage V_d (V)	Sheet carrier charge density (cm^{-2})	
		Two Dimensional Electron Gas (2DEG*e^{17})	Two Dimensional Hole Gas (2DEG*e^{17})
1	-2	1.04835	1.03125
2	-1	1.42276	1.4084
3	0	1.79717	1.78554
4	1	2.17158	2.16269
5	2	2.54599	2.53984
6	3	2.9204	2.91698
7	4	3.29481	3.29413

Table 2. Statistical analysis of comparison of two-dimensional electron gas (2DEG) and two-dimensional hole gas (2DHG) Group statistics

	GROUP	N	Mean	Std.deviation	Std.error Mean
Sheet carrier charge density	2DEG	7	$2.1716e^{17}$	$8.0881e^{17}$	$3.05704e^{17}$
	2DHG	7	$2.1627e^{17}$	$8.14729e^{17}$	$3.07939e^{17}$

Table 3. Independent sample T-test t is performed for the two groups for significance and standard error determination of sheet carrier charge density improvement for two-dimensional electron gas (2DEG) and two-dimensional hole gas (2DHG). P value is 0.0098 ($p<0.05$) and it is considered to be statistically significant.

Independent Sample Test										
		Levene's Test for Equality of Variances		T-test for equality of Means						
		F	Sig.	t	df	Sig. (2-tailed)	Mean differance	Std. Error differance	95% confidence Interval of the differance	
									Lower	Upper
Sheet carrier charge density improve -ment	Equal variances assumed	0.00	0.0098	0.020	12	0.00984	$8.9e^{14}$	$4.3e^{16}$	$-9.4e^{16}$	$9.4e^{16}$
	Equal variances not assumed			0.020	11.99	0.0984	$8.9e^{16}$	$4.3e^{14}$	$-9.4e^{16}$	$9.4e^{16}$

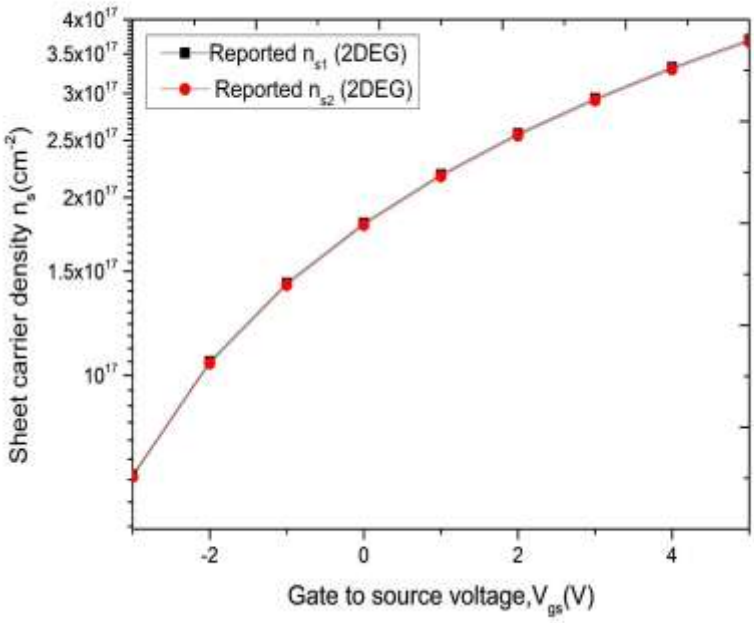

Fig. 1. Comparison of two-dimensional electron gas (2DEG) with respect to gate to source voltage based on AlGaN/GaN based high electron mobility transistors (HEMT).

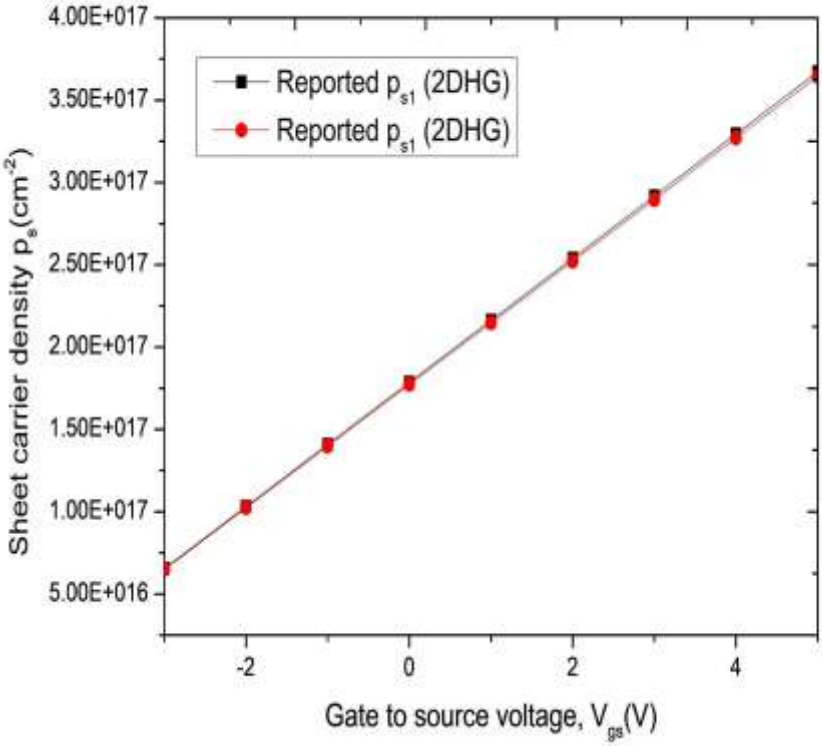

Fig. 2. Comparison of two-dimensional hole gas (2DHG) with respect to the gate to source voltage based on high electron mobility transistors (HEMT).

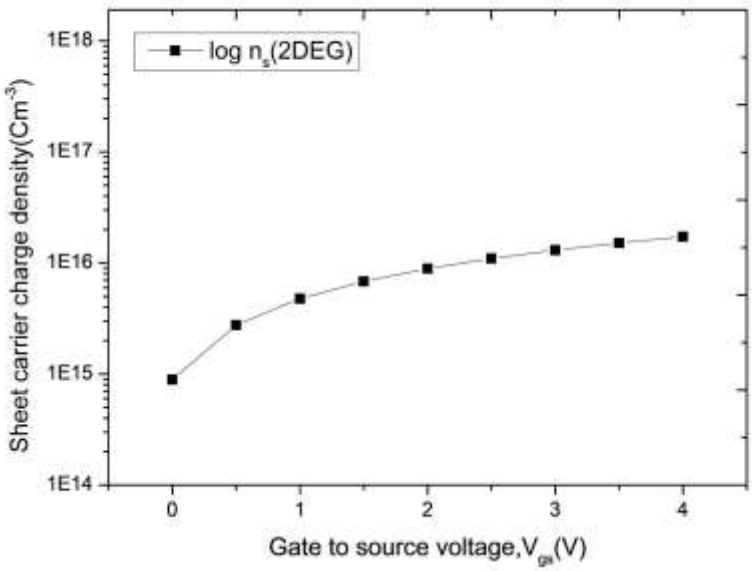

Fig. 3. Comparison of sheet carrier charge density with respect to the gate to source voltage, Vgs(V) based on high electron mobility transistors (HEMT).

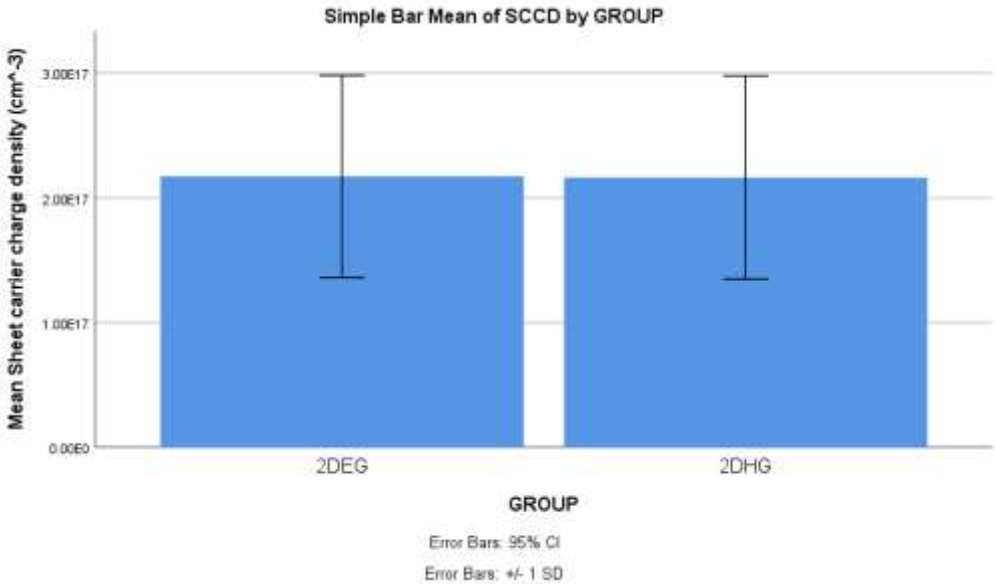

Fig. 4. Bar graph comparison of Two dimensional electron gas (2DEG) and Two dimensional hole gas (2DHG) in terms of mean sheet carrier charge density. X axis: Two dimensional electron gas vs Two dimensional hole gas. Y axis: Mean sheet carrier charge density of detection ± 1 SD.