Reduction of Current Collapse and Leakage Current in AlGaN/GaN Double Channel HEMT

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Abstract: ***A spectrum of phenomena related to the reliability of AlGaN/GaN double channel high-electron-mobility transistors (HEMT) are investigated. The focus is on trap related phenomena that lead to decrease in the power output i.e. the current collapse. It is widely believed that the current collapse is caused by a virtual gate, i.e. electrons leaked to the surface of the device. Virtual gate has a similar impact on the I-V curve as is observed during the current collapse. If the region of the trapped charge means gate length is relatively small and the doping concentration is high the current collapse was suppressed but increases the leakage current. . In this paper, we report a double channel HEMT with low electron density in the second channel. Wider high trans-conductance region is obtained compared with single-channel HEMT.We have demonstrated the reduction of current collapse and leakage current in AlGaN/GaN double channel (HEMTs) by using extending in gate length, decrement of doping concentration and drain voltages was calibrated. The 2D ATLAS silvaco simulations are done and that simulation model is validated with 28nm and 18nm technology node .The transfer characteristics, threshold voltage, and drive capability of AlGaN/GaN double channel HEMT structure is analysed.***

Keywords: HEMTs, Gallium nitride, Aluminium gallium nitride, Aluminium gallium nitride/Gallium nitride HEMT, Current Collapse, Cutoff frequency, Radio frequency, field-effect transistors, channel mobility

1. Introduction

Traditionally, AlGaN-based and GaN-based HEMTs have been the premier FET devices for radio frequency (RF) applications. On the other hand, Conventional MOSFETs have been considered as obsolete devices that could not compete with AlGaN/GaN HEMTs.

A new generation of high speed – high frequency devices is required. For future Military and space application, it is more effective as compared to conventional MOSFET Wide Band Gap Semiconductors like Gallium Nitride is generally used for high frequencyor Microwave applications[1] [3].

AlGaN/GaN High Electron Mobility Transistor (HEMT) is termed as hetro-structure field effect transistor (HFET)[2].The hetro-structure consisting of two or more layers of semiconductor materials, each of layers with different bandgaps, and whose crystal structure is similar.

AlGaN/GaN HEMTs have some material advantages such as high breakdown voltage, high electron peak velocity, and high electron density that is why it has received much attention for high-frequency and high-power applications because of the even though much progress has been achieved in the high-frequency performances, there are still some issues, which should be addressed, such as current collapse [4].

The current collapse in AlGaN/GaN HEMT due to the HEMT utilizes a hetero-structure to create a potential well perpendicular to the hetero-interface[5]. The electrons that are confined to this potential well are free to move parallel to the interface, forming a 2DEG.[6].Nitride Devices are better than Arsenide's because Arsenide's do not possess spontaneous polarization and the piezoelectric constants are an order of magnitude lower than those of nitrides. Therefore, un-doped Arsenide hetero-structures cannot induce high 2DEG. Even with doping, the conventional GaAs based HEMTs can achieve 2DEG density of approximately 2×10^{12} cm^{-2}. However, intentional doping is not necessary for GaN based devices, since, due to the high polarization, the 2DEG densities are already on the order of $10^{13} cm^{-2}$.[7] Moreover, doping could reduce the electron mobility via scattering. The 2DEG creates the channel, which leads current in the device [6],[7].

The polarization charge induces large electric field in the AlGaN layer. For thin AlGaN barrier, the trap energy level is below the Fermi level and the states are filled as the barrier reaches a critical thickness, the trap level hits the Fermi level and the traps start to empty and become positively charged and, due to the strong electric field, the electrons transfer to the channel[8]. In reality, the bands in GaN change with the barrier thickness.

For a thin barrier, all electrons are in the traps and not in the channel; hence the conduction band will be above the Fermi level and will not bend.[9] Large negative $V_G$bias will induce high electric field close to the gate and the electrons form the gate leak to the empty surface states, create a "virtual gate" and deplete the channel [10],[11].

The conducting channel (under the hetero interface, between the source and drain terminals) can be viewed as a resistance. For small drain-source voltage V_D, the drain current $I_D$is approximately linear. When a negative voltage is applied to the gate, the electrons are partially depleted from the channel and its resistance increases. As the negative gate voltageV_D is increased, a threshold voltage $V_T$is reached. At the threshold, the channel is closed, i.e., completely depleted of electrons, and the $I_D$drops to zero. This condition is called pinch-off[12].

In pulsed operation, the gate voltage changes abruptly and since the response of the trapped electrons is not immediate, it leads to current collapse phenomenon.

The AlGaN/GaN high electron mobility transistor (HEMT) is an excellent candidate for applications in high power electronics. Superior performance of the AlGaN/GaN HEMT relies on the high breakdown electric field of nitride semiconductors and the polarization effect-induced high-density high-mobility two-dimensional electron gas (2DEG) at the AlGaN/GaN interface. AlGaN/GaN double-channel HEMTs were constructed to enhance the current drive and to alleviate the current collapse.[4]

2. Device Structure

The Structure of AlGaN/GaNdouble-channelHigh-Electron Mobility Transistors based on their design.

The work is done on 28nm and 18nmtechnology node using 2D ATLAS silvaco tool. The Physical parameters for the AlGaN/GaNdouble-channel HEMT have been specified as shown in table 1:

Table 1

Physical Parameter	*Value*
Technology node	28nm
Gate oxide thickness	0.5nm
Gate thickness	4nm
Source/Drain doping	1.5e17cm-3
Gate length	20nm
Substrate doping	2e21cm-3
Substrate thickness	6nm
Box thickness	18nm

In the below Fig (1) the structure of AlGaN/GaN double-channelHEMT, then, and the last is in Fig(2) doping declaration.

The most widely used substrates in the GaN technology are Si, SiC and sapphire (Al2O3).

Si lattice mismatch with GaN is 17% and its lattice constant is larger than that of GaN. Hence, GaN grows with a tensile stress, which leads to creation of crystal defects, which reduce the performance of the device.Si possesses an acceptable thermal conductivity and is reasonably priced.

Lattice mismatch between SiC and GaN is 4%. Its very good thermal conductivity and density is under $3x10^{8}cm^{-2}$. It is the preferred one for high frequency applications. Unfortunately, SiC is very expensive. In this paper, GaN used Al2O3substrate that act as insulator. Sapphire has the largest lattice mismatch with GaN.

Depending on their relative orientation to each other, the mismatch is between 14% and 23%.Sapphirepossesses an acceptable thermal conductivity. The advantage of this substrate is that it is cheap and available in wafers with large diameters.

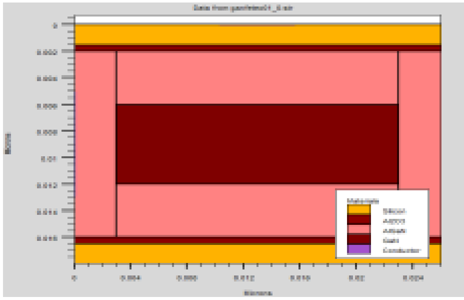

Figure 1: The Structure of ALGAN/GAN double-channel HEMT

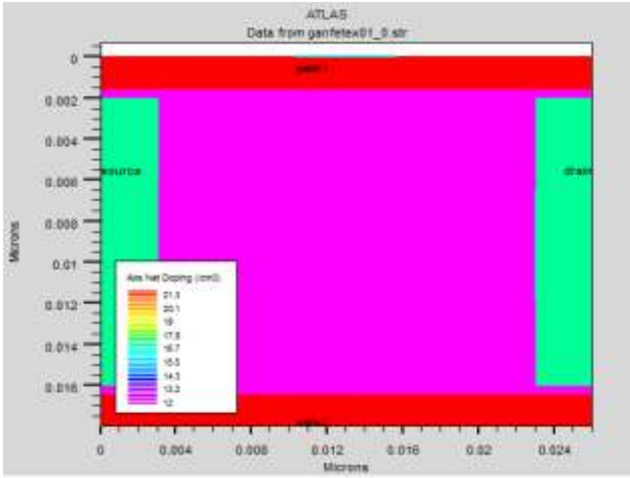

Figure 2: The doping declaration of AlGaN/GaN double-channelHEMT

3. Simulation and Result Discussion

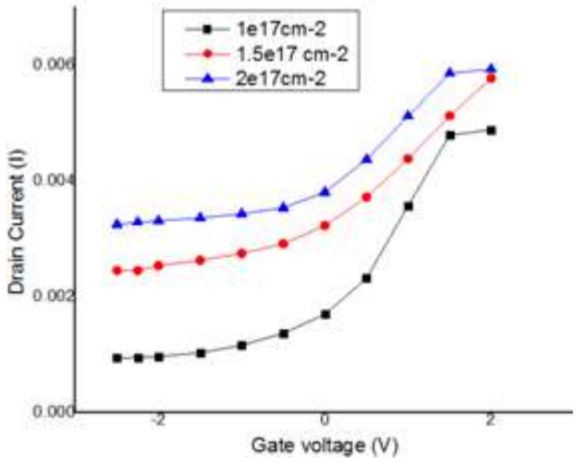

Figure 3: V_G-I_D characteristics for different values of surface electron density

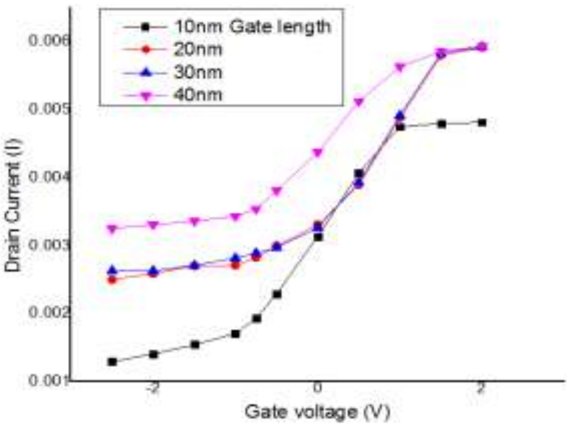

Figure 4: V_G-I_D characteristics for different values of Gate length

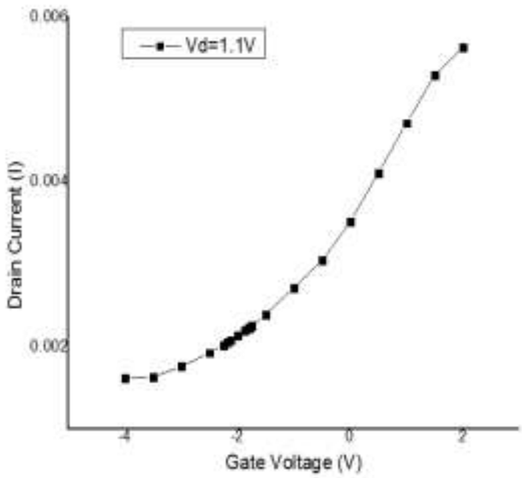

Figure 5: V_G-I_D characteristics of AlGaN/GaN double-channel HEMT V_D=1.1V.

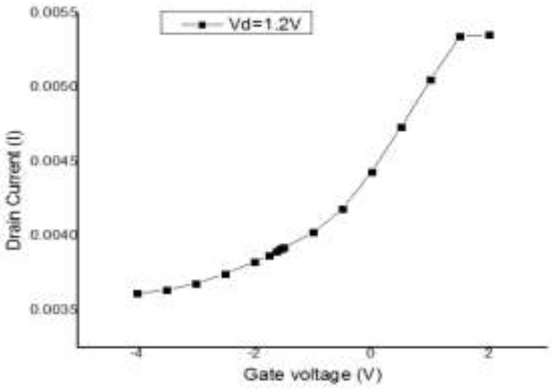

Figure 6: V_G-I_D characteristics of AlGaN/GaN double-channel HEMT with V_D=1.2V.

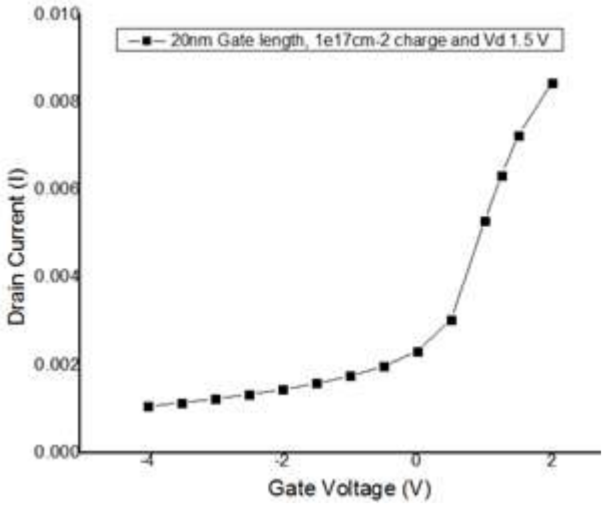

Figure 7: V_G-I_D characteristics of AlGaN/GaN double-channel HEMT with $V_{D=}$ 1.5V

Initial simulations used rectangular charge slabs, which were placed on the source and drain sides of the gate and varied in length and charge density.[13]

The mechanism responsible for the current collapse and higher leakage current due to the strong electric field, through the means of the conduct electricity, the electrons leak to the surface of the gate and electro statically deplete the channel and hence cause reduction of the saturation current. This is the primary mechanism [14].

The secondary mechanism is that the electrons at the surface create additional electric field which forces the later leaked electrons to transfer to the traps in the bulk and to the AlGaN/GaN interface.[15] During a stress test, in the region of the high electric field and therefore traps are created. This leads to a permanently degraded device and reduced current in subsequent measurement [16][17].

There are different way to reduce the current collapse and leakage current in AlGaN/GaN double-channelHEMT that are:

1) The reduction ofdoping concentration that leads to increases of the saturation current and decreases the current collapse.
2) When electrons are move towards to source and the region is small and drain current is high then electrons are traps and lead the current collapse, so here we will extent the length of gate through which the electrons are move drain to source without traps and minimize the current collapse.

In Figure (3),In this I_D-V_G characteristics for different values of surface electron density, $1x10^{17}cm^{-2}$, $1.5x10^{17}cm^{-2}$ and $2x10^{17}cm^{-2}$ placed at the edges of the gate.The sheet charge density $1.5\times10^{17}cm^{-2}$ and drain voltage is V_D=1.1V the region of the trapped charge, was enough to change the access resistance, as seen from the I_D-V_G graph. Therefore, this suggests that, to achieve the change in the slope seen in the experimental data, we need to decreases the amount of charge leads to increases of the saturation current, and decreases the current collapse.

In Figure (4), We have used a previously reported, the charge density $1.5\times10^{17}cm^{-2}$ impact of the length (10-40 nm) of the region at a constant surface electron density, 1.5×10^{17} $cm^{-2}$and Drain current I_D is 1.1V investigated. In which the electrons are move towards to source, when the region is small and drain current is high then electrons are traps and leads the current collapse, so here we will used sufficient length of region that is 20nm gate length through which the electrons are move drain to source without traps.

In both cases, change the slope of the linear region, necessary to fit the experimental I_D –V_G characteristics. Further on, we investigate the impact of the charge on the drain and source sides of the gate on I_D –V_G.

In Figure (5), for drain voltages V_D=1.1V the region of trapped charge and that access resistance .I_D-V_G graph not achieve linear slope of the simulation data and that shows the higher leakage current.

In Figure (6), for drain voltages V_D=1.2Vth region of also trapped charge and that access resistance.

In Figure (7), The Drain Voltage V_D=1.5 V charge in both areas has the same effect on the linear region.That Linear region shows the reduction in current collapse and lower leakage current.

For higher drain voltages, the current is limited.

4. Conclusion

The aim of this paper was to investigate some of the processes reduce the current collapse in AlGaN/GaN double-channel HEMTs. The current collapse are trap-related phenomena and trapping mainly at the surface of the device. The material parameters of AlGaN/GaN focus on the properties that make this class of materials distinct from the conventional, such as structure with the consequence of spontaneous and piezoelectric polarization. This results in a bound charge at AlGaN/GaN hetero-structure interface, which gives rise to a large 2DEG density in the channel without the need for doping.The relation between the electrical properties that is the electric field and piezoelectric are related direct and converse piezoelectric effects were introduced with the implication of the electric field induced strain and stress.

Large negative $V_G$bias will induce high electric field close to the gate and the electrons form the gate leak to the empty surface states, create a “virtual gate” and deplete the channel.Voltage applied to the gate modifies the electric field at the edges of the gate and in the channel under the gate significantly. This leads to strain, induced via the converse piezoelectric effect, being dependent on the gate voltage. From this follows that the piezoelectric polarization and hence the bound charge, induced in the bulk and modified at the hetero-junction interface, will vary with the applied voltage.

The current collapse is traps related phenomena, investigated the impact of electrons, and trapped at the surface of the device and under its gate, on the I-V characteristics. We eventually found the values of the fitting parameters that reproduced the measured pulsed I-V characteristics and showing current collapse accurately. The collapse was suppressed bywide range of gate length, decrement of doping concentration and calibrated drain voltages

5. Future Work

The work in this paper would be to simulate the I_D-V_G characteristics of a degraded device searching for the appropriate distribution of the trapped charge irrespective of the underlying mechanism, i.e. irrespective of the exact defect distribution, and using the stress distribution.

The simulation of the leakage of the electrons from the gate to the device performed took only primary leakage mechanism into account, i.e., to the surface of the device. To obtain a more realistic picture of the charge distribution, one could simulate the leakage including the secondary leakage mechanism, i.e. to the bulk of the device [18].

Another improvement of the work done in this paper would be further automation of the simulations. E.g. currently, the procedure is to perform all simulations and evaluate [19]. A more efficient method would of course be to perform one or several simulations, evaluate the results, modify the parameters accordingly and perform the simulations until a goal, i.e. a calibration of some sort, is achieved [20]. This could be done using either a gradient method, which is easier to code, but has the disadvantage that it may get stuck in a local extreme, or using a genetic algorithm, which is more demanding on computational time, but scans the phase space of parameters more efficiently.

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