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Oxygen addition to fluorine based SiN etch process: Impact on the electrical properties of AlGaN/GaN 2DEG and transistor characteristics

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ABSTRACT

Early passivated AlGaN/GaN heterostructure field effect transistors (HFETs) have shown superior device performance compared to their unpassivated counterparts. The opening of gate trenches in the passivation layer by a fluorine based dry-etch process is the crucial step to obtain high-performance devices. Even though oxygen addition to this process has been reported, its effect on the device characteristics has not been studied yet. In this paper, we report the impact of oxygen addition to a fluorine based plasma on two-dimensional electron gas (2DEG) properties as well as on device characteristics of passivated AlGaN/GaN HFETs. It is shown that oxygen addition reduces the fluorine-induced degradation of the 2DEG density. Yet, recovery of the 2DEG density is prevented. Additionally, it is shown that oxygen addition increases the current collapse and therefore decreases the RF performance.

1. Introduction

The improvement of the device performance for nitride-based heterostructure field effect transistors (HFET) by SiN passivation has been known for more than 10 years [1]. The easiest fabrication method of passivation is to apply the passivation layer as last step. Nonetheless, an application of SiN before the gate metallisation can lead to a further increase in device performance. In addition to protecting the semiconductor surface from damage and contamination, it allows to shape the edge of the gate foot via a dry etch process. This enables the reduction of the maximum electric field at the drain edge of the gate, yielding superior device behaviour compared to non shaped gates with respect to current slump [2].

The necessary opening of gate trenches in the SiN is typically performed with a dry etch process based on fluorine. There has been a lot of effort to study the effect of fluorine based plasmas on device properties [3,4]. It is widely accepted that fluorine is incorporated in the barrier. Thus, it enables the depletion of the 2DEG in a manner that a once normally-on device can even be turned into a normally-off device [4–6]. Also the addition of oxygen has already been reported [4,6,7]. Oxygen is known to improve the removal of organic residue and non-volatile fluorinated reaction products and appears therefore a reasonable addition to the GaN device process. Yet, the effect of oxygen has not been investigated in detail.

In this paper, we show how oxygen can influence not only the properties of the two-dimensional electron gas (2DEG), but also the transistor performance regarding DC results, pulsed-IV results and RF-power measurements.

2. Experimental

Material grown by metal organic chemical vapour deposition (MOCVD) was used for the experiments discussed here. The HFET structure is based on a GaN/transition layer stack on silicon (1 1 1) substrate. Thereon is a 17.5 nm thick $Al_{0.26}Ga_{0.74}N$ barrier layer with a 2 nm GaN capping layer on top.

The complete HFET process with an early deposited passivation layer includes the gate trench etch. In order to ensure a complete SiN removal, a certain degree of overetch is needed. Consequently, the semiconductor surface will be exposed to the plasma process

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directly and the 2DEG properties will be impacted by the interaction with the gaseous species.

In order to understand the effect of this interaction, preliminary experiments were performed on unpassivated 5 × 5 mm² AlGaN/GaN samples in van-der-Pauw configuration. Ohmic (Ti/Al/Ni/Au) contacts were deposited via electron beam (e-beam) evaporation using a shadow mask. Thereafter, annealing in a rapid thermal annealer (RTA) at 825 °C was performed.

To investigate the influence of etch chemistries on the 2DEG characteristics, the samples were treated either with a CF_4/O_2 or CF_4 plasma in an ICP-RIE chamber. Applied gas flow rates were 20/2 sccm and 20 sccm, respectively. After the etch treatment, van-der-Pauw and Hall effect measurements were carried out on the samples. For investigation of possible 2DEG recovery effects, additional annealing experiments at 400 °C in nitrogen atmosphere were performed in an RTA chamber.

Following the above experiments, two samples (A and B) were processed to fully functional HFETs enabling characterisation at the device level. Equivalent epitaxial material was used. Devices were mesa-isolated by a chlorine-based inductively coupled plasma reactive ion etch (ICP-RIE) process. The ohmic contact stack was the same as before. The resulting contact resistance (R_c) was measured to be 0.55 Ωmm. Afterwards, a plasma enhanced chemical vapour deposition (PECVD) process step was used to passivate the samples with 110 nm SiN. To open the gate trenches in the SiN, a fluorine based ICP-RIE dry etch process based on results achieved above was applied. For sample A, the SiN was etched completely with a CF_4/O_2 plasma, while for sample B a CF_4-only process was applied. Yet, to enhance the removal of unwanted organic residues, oxygen was added for the first part of the recess and switched off just before the GaN surface was uncovered. The achieved sidewall angle in the SiN was 60° for both processes. After the gate trench opening, Ni/Au-based gate contacts were deposited via e-beam evaporation. The gate length was measured to be 1.30 µm. Resulting gate drain and gate-source separation was 2.35 and 1.35 µm, respectively. Finally, an annealing step based on the results achieved from the 5 × 5 mm² samples was performed in an RTA. For the characterisation, van-der-Pauw and Hall effect measurements, DC measurements, pulsed IV measurements, as well as large signal RF-measurements were performed.

3. Results and discussion

3.1. AlGaN/GaN van-der-Pauw samples (5 × 5 mm²)

The impact of different plasma processes on the sheet carrier concentration of the 5 × 5 mm² samples is depicted in Fig. 1a. To investigate the effect of overetching, the samples were not passivated. In order to be able to apply the results to the actual transistor process, the *x*-axis is normalised to the corresponding SiN etch depth with respect to 110 nm SiN height. Since, no SiN was applied, the time can be seen as virtual overetching. SiN etch rates varied from 50 nm/min for the process with 50 W ICP power, 100 V V_{bias} down to about 5 nm/min for the 20 W ICP power, 17 V V_{bias} processes. That means an overetch of roughly 20% (25 nm) would give treatment times of 30 s and 300 s for the respective processes. The *y*-axis is normalised to the original sheet carrier concentration (n_{s0}) of each sample n_{s0} is ca. 7.5 × 10^{12} cm^{-2} for all samples. The experiments show that the high voltage processes yield the same results, irrespective of the ICP power level used. For both high and low ICP power the reduction in n_s is linear with time. Nonetheless, taking into account the higher etch rate of the high power process (squares), for this process n_s is reduced within a shorter period of time.

Comparing the two processes with low ICP power and low ion energy (triangle and star), we observe a different behaviour of the n_s reduction. Here, n_s decreases exponentially. In particular, for the process with oxygen (triangle), the decrease seems to be softer than for the process without oxygen (star).

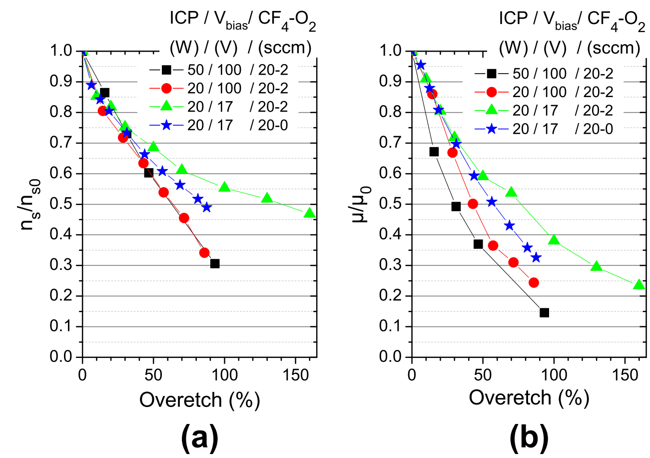

Fig. 1. Normalised n_s (left) and μ (right) over time for different etch processes, *x*-axis is normalised to overetching time in percentage.

Analysing the different shape of the graphs, it appears that two fundamentally different mechanisms must be responsible for the observed behaviour. Fluorine is known to directly affect the amount of charges in the 2DEG [3,4,8]. Therefore, for the processes with high ion energy, the linear decrease might be related to an implantation-like incorporation of fluorine ions into the barrier. For implantations, the depth of the Gaussian distribution of implanted species depends linearly on the implanted dose, controlled in our case by the (over) etch time, resulting in the linear decrease observed for high powers.

For the processes with low ion energy, the exponential decrease in n_s indicates a diffusion-like mechanism. Since the bias voltage is very low, it has to be assumed that fluorine is incorporated only into the first atomic layers of the AlGaN barrier. Studies from other groups show that a shallow implantation occurs even for higher ion energies [8,9]. Furthermore, the difference in steepness of the slope can be explained by a reduced physical component of etching, yielding a less damaged lattice of the barrier. Therefore, n_s stays at higher levels for prolonged etching times.

In addition, by comparing the triangle with the star curve, it is obvious that the added oxygen reduces the decrease of n_s over time. This cannot be correlated to a decreased amount of active fluorine ions in the plasma. The amount of ionised fluorine should be higher when oxygen is added. This is caused by a fast recombination of fluorine radicals and atoms back to CF_4 or C_2F_6 under oxygen absence [10]. Therefore, it must be assumed that oxygen addition leads to an oxygen terminated surface or even a thin oxide-like layer on the GaN surface which could then prevent the incorporation of fluorine [11].

As can be seen in Fig. 1b, mobility (μ) degradation is also observed. Again, the values are normalised to the original value μ_0, which is approx. 1600 cm²/Vs. The same trend as before between the processes is recognised. Yet, it is more difficult to differentiate possible effects. In all cases the degradation appears to be correlated with both lattice damage as well as with the fluorine induced depletion of the 2DEG, and therefore with a delocalisation of the carriers.

In order to evaluate the stability of the observed changes, annealing experiments at 400 °C under nitrogen atmosphere at 800 mbar were carried out on samples treated with processes with 20 W ICP power and V_{bias} = 100 V. Before annealing, the samples were treated in the ICP chamber for 32 s, corresponding to an overetch of approximately 10%.