Impact of N_2 Plasma Power Discharge on AlGaN/GaN HEMT Performance

M.-Fátima Romero, Ana Jiménez, Fernando González-Posada Flores, Sara Martín-Horcajo, Fernando Calle and Elías Muñoz

***Abstract*—The effects of power and time conditions of *in situ* N_2 plasma treatment, prior to silicon nitride (SiN) passivation, were investigated on an AlGaN/GaN high-electron mobility transistor (HEMT). These studies reveal that N_2 plasma power is a critical parameter to control the SiN/AlGaN interface quality, which directly affects the 2-D electron gas density. Significant enhancement in the HEMT characteristics was observed by using a low power N_2 plasma pretreatment. In contrast, a marked gradual reduction in the maximum drain–source current density ($I_{DS\,\max}$) and maximum transconductance ($g_{m\,\max}$), as well as in f_T and $f_{\max}$, was observed as the N_2 plasma power increases (up to 40% decrease for 210 W). Different mechanisms were proposed to be dominant as a function of the discharge power range. A good correlation was observed between the device electrical characteristics and the surface assessment by atomic force microscopy and Kelvin force microscopy techniques.**

***Index Terms*—AlGaN/GaN high-electron mobility transistors (HEMTs), passivation, plasma treatment, silicon nitride (SiN), surface.**

I. Introduction

GaN AND related compounds are promising semiconductors for next-generation high-frequency and high-power devices, particularly at high temperature and high voltage operation [1], [2]. Their wideband gap allows high breakdown voltage, high saturation current, and strong radiation hardness capabilities in an AlGaN/GaN high-electron mobility transistor (HEMT), which make them potential candidates for many different applications, such as wireless communications [3], future power electronic converters [4], aerospace electronics [5], etc. Although significant progresses have been done leading to record frequency performance with 300-GHz $f_{\max}$ [6], there are still several problems to be solved concerning mainly reliability and stability [7]. One key issue is related to the surface electronic states that are strongly responsible for RF dispersion (or current collapse), preventing their widespread use and leading to low reliability [8]. Recently, it was shown that not only a suitable dielectric layer is needed to mitigate RF dispersion in AlGaN/GaN HEMTs, but the use of a plasma surface pretreatment could also play a crucial role. The most employed dielectric for this aim is silicon nitride (SiN), which is used with or without pretreatments. In that case, several pretreatments have been tried such as N_2 [9], [10], NH_3 [10], [11], $O_2 + CF_4$ [12], and $O_2 + SF_6$ [13]. In particular, the use of a N_2 plasma pretreatment has been recently reported, although not only to mitigate RF dispersion prior to the SiN passivation layer, but also for different aims such as to reduce gate leakage current in MISHEMT devices [14], prior to ohmic contact metallization to lower contact resistance [15], or to minimize surface recovery after etching damage [16]. The different goals for using a N_2 plasma pretreatment and the wide range of plasma techniques and conditions make its effects on the surface properties to be still under discussion. Some reports have shown that a nitride plasma-based surface treatment previous to passivation could improve device performance, probably due to the reduction in carbon and oxides over the AlGaN surfaces [10], [17], [18]. In contrast, other authors observed that plasma produced detrimental effects in an AlGaN/GaN HEMT [13] or the formation of creation of a N_2-deficient surface [15], suggesting that the plasma discharge conditions should play a critical role in the surface preparation.

This work focuses on the *in situ* N_2 plasma treatment prior to the SiN passivation layer, deposited by plasma-enhanced chemical vapor deposition (PE-CVD). In a previous work, we reported the beneficial effects of using a low power N_2 plasma to mitigate current collapse by reducing surface states on AlGaN/GaN HEMTs [9]. This work aims to identify how critical are the power and exposure time used during the N_2 plasma discharge that directly affect the GaN-based surface, in correlation to the AlGaN/GaN HEMT electrical characteristics. Therefore, it contributes to clarify the mechanisms that control the GaN-based surface properties, which are the basis for the new generation of GaN-based devices, including sensors, high-power and high-frequency HEMT devices fabrication.

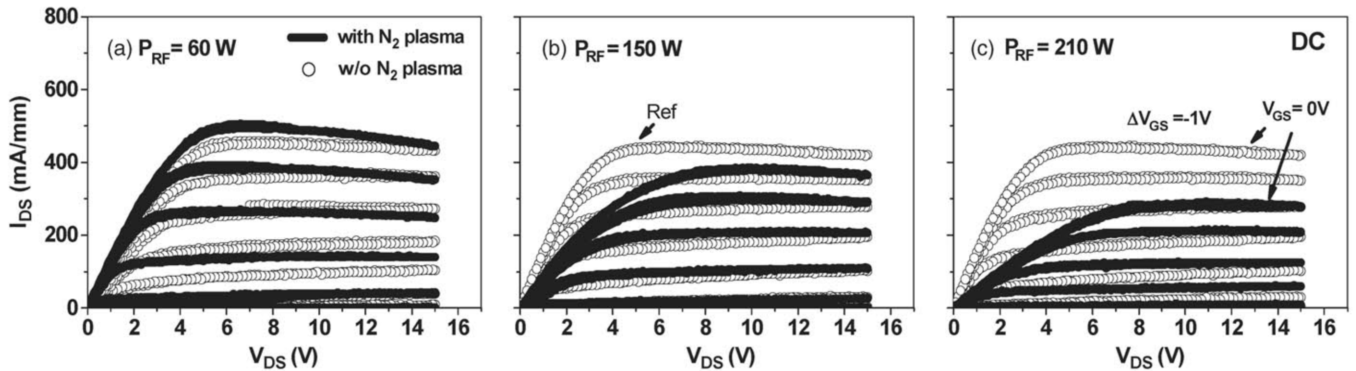

Fig. 1. DC $I_{DS}-V_{DS}-V_{GS}$ characteristics of the AlGaN/GaN HEMT (solid lines) passivated with SiN and the N_2 plasma pretreatment at (a) 60, (b) 150, and (c) 210 W, during 1 min. Devices (open circles) passivated with SiN but without any plasma pretreatment are used as a reference. $V_{GS} = -6$ to 0 V, $\Delta V_{GS} = 1$ V. $L_G = 1.3$ μm.

In the next section, the experimental procedure is described. In Section III, the effects of different power and time parameters during the plasma discharge are discussed in relation to electrical characterization of HEMT devices and surface analysis measurements of AlGaN/GaN heterostructures. Section IV is devoted to describe a model of the dominant mechanisms as a function of the N_2 plasma power discharge. Finally, in Section V, the conclusions of this work are summarized.

II. Experimental Procedure

Five AlGaN/GaN structure wafers provided by the same epitaxial source were used in this study. The HEMT structure consisted of (28–30) nm of $Al_{0.28}Ga_{0.72}N$ on 1.2 μm of GaN grown on 4H-SiC or sapphire substrate by metal–organic vapor phase epitaxy. A nominal carrier concentration varying from 9.3×10^{12} to 1.1×10^{13} cm^{-2} was intended. Drain and source ohmic contacts were made by alloying Ti/Al/Ti/Au. Schottky gates were fabricated by optical Pt/Ti/Au and e-beam Ni/Au lithographies, with a 1.3-μm length and two widths of 75 and 150 μm. The standard passivation processing consisted in a SiN layer deposition at 300 °C in a conventional RF PECVD system using SiH_4 and NH_3 as precursors. A slightly N-rich SiN layer was obtained, with $n = 1.83$ and $\varepsilon_r = 7.0$ as determined by ellipsometry. In this study, each wafer with HEMT devices was divided into several pieces that followed a different surface pretreatment prior to the standard passivation. After a wet cleaning with NH_4OH at 50 °C, each piece was exposed to a N_2 plasma discharge at 200 °C followed by the standard SiN deposition in the same reactor without breaking the vacuum. The N_2 plasma power was varied from low power (60 W, where a minimum stable plasma is obtained) to medium (150 W) and high power (210 W). The N_2 plasma discharge duration was increased from 1 to 20 min for the lowest power. One of the pieces was used as reference without any previous *in situ* cleaning or plasma pretreatment of the surface before the passivation.

The HEMT devices were characterized by dc and pulsed $I-V$ measurements from $V_{GS} = -6$ V (1 V lower than pinchoff) to 0 V (open channel). Gate pulse period was varied from 100 ms to 1 μs, with a constant 50% duty cycle. Moreover, gate lag measurements were performed by fixing V_{DS} at 5.5 V and applying pulsed V_{GS} excitation from OFF- to ON-state, as detailed by Meneghesso *et al.* [19]. Besides, S-parameter measurements were also carried out to evaluate f_T and $f_{\max}$.

In order to analyze the N_2 plasma impact on the device surface morphology and surface potential, AlGaN/GaN heterostructures and GaN (n-type) templates were analyzed by atomic force microscopy (AFM) in tapping mode and Kelvin probe force microscopy (KPFM) after each N_2 plasma pretreatment. It is worth mentioning that by using KPFM, in addition to the AFM technique, the electrical effects of the N_2 plasma pretreatment were possible to be analyzed even with the *in situ* SiN passivation film. This provides a significant advantage over other surface analysis techniques, in order to avoid uncontrollable surface oxidations or contamination after the N_2 plasma treatment that may induce changes in the surface potential values [20].

III. Results and Discussion

A. Electrical Characterization

The typical dc output characteristics of AlGaN/GaN HEMTs using the N_2 plasma pretreatment for 1 min at 60, 150, and 210 W RF power, compared with an equivalent transistor without any plasma pretreatment, are shown in Fig. 1. Whereas a slight increase in the current and transconductance is observed after a 60-W plasma treatment, a gradual and strong reduction in $I_{DS\max}$ and $g_{m\max}$, up to 33%, was measured as the N_2 plasma pretreatment power increased. The drop in the current density and the positive shift in the knee voltage mean that the access resistance increases with the plasma pretreatment power, which seriously affects high-frequency device performance [21]. Electrical measurements using the transfer line method with a passivated surface reveal that the contact resistance values (R_c) hardly change with the plasma pretreatment ($R_c =$ 0.5–0.9 $\Omega \cdot$ mm), whereas the sheet resistance (R_{sheet}) value rapidly increases with the N_2 plasma power applied. In fact, for the high power (210 W) plasma, R_{sheet} values reach around 2500 Ω/sq, which is ~5 times higher than the case with the lower power (60 W) plasma ($R_{\text{sheet}} = 480$ Ω/sq), confirming that the AlGaN surface in the active region is affected by the plasma treatment power [22]. These results highlight a strong and gradual reduction in the 2-D electron gas (2DEG) charge density in the channel and mobility as the N_2 plasma power

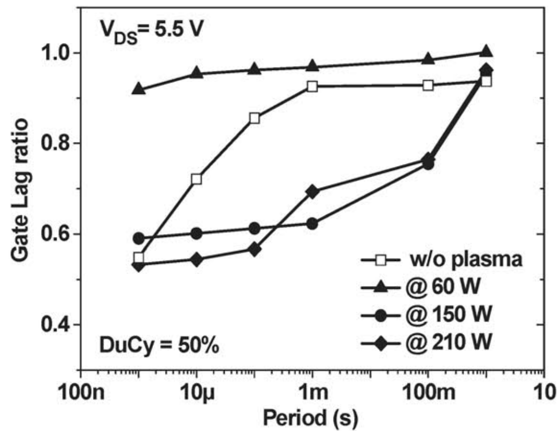

Fig. 2. GLR versus gate pulse period (constant duty cycle of 50%, V_{DS} = 5.5 V) of samples (open squares) without plasma pretreatment and with N_2 plasma pretreatment at (black triangles) 60, (black circles) 150, and (black squares) 210 W. Solid lines are guidelines for the eye.

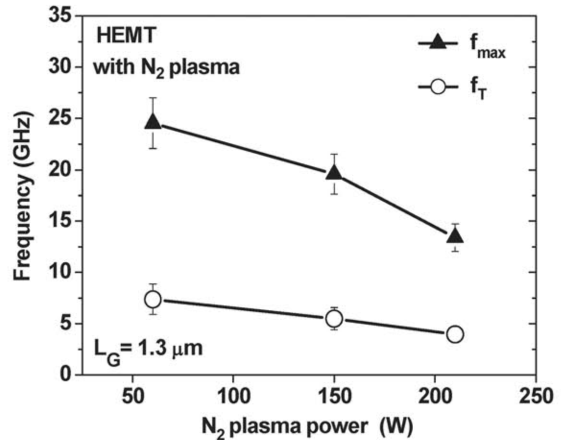

Fig. 3. (Black triangles) Maximum frequency $f_{\max}$ and (open circles) cutoff frequency f_T of samples passivated with SiN and N_2 plasma pretreatment at 60, 150, and 210 W, respectively. Solid lines are guidelines for the eye.

increases from low (60 W) to high (250 W) plasma powers. In addition, these gradual reductions are consistent with the drop measured in the dc $I_{DS\max}$ and the positive shift of the threshold voltage (V_{th}) from −4.42, to −4.07, and to −3.82 V, at 60, 150, and 210 W, respectively.

To further investigate the influence of the N_2 plasma power in the trapping of charges in HEMT devices, collapse measurements were carried out. Pulsed output characteristics on AlGaN/GaN HEMTs showed similar behavior as in dc performance. $I_{DS\max}$ values increased for low plasma power and decreased as the plasma power was higher. In fact, devices using the lowest power plasma pretreatment (60 W) showed about 12% higher $I_{DS\max}$ than those without any plasma pretreatment, which is in good agreement with previous results [9]. In Fig. 2, the gate lag ratio (GLR), which is defined as the ratio of the pulsed I_{DS} value in steady state to the dc I_{DS} value at $V_{DS} = 5.5$ V, is presented for different pulse periods. For long periods, i.e., long pulse widths (around 1 ms–1 s), the GLR is almost constant for the untreated devices and for the low power N_2 plasma pretreatment. Noteworthy, the GLR is almost equal to 1 (minimum current collapse) for the low power N_2 plasma pretreatment and remains constant as the pulse width is narrowing. In comparison, the untreated surface device presents a worse GLR with a shorter pulse width (< 1 ms), i.e., a worse high-frequency performance. This result highlights the beneficial effects of the low power N_2 plasma pretreatment to mitigate current collapse by reducing surface trap charges in the active region and improve the high-frequency performance HEMT devices [9], [10]. In contrast, in the case of higher plasma power, the GLR rapidly moves away from 1 (minimum current collapse) for pulse period narrower than 500 ms up to the shortest pulses (500 ns). This suggests that the high N_2 plasma power induces trap charges generation on the AlGaN surface with charge emission time constants above 250 ns, which is consistent with Meneghesso *et al.* [19].

The impact of the N_2 plasma power was also noticeable in RF characterization. At low plasma power, no degradation in f_T and $f_{\max}$ was shown, and a small (∼5%) increase in $f_{\max}$ with respect to the case without a N_2 plasma pretreatment was found. However, a similar 40% degradation in f_T and $f_{\max}$ for the highest plasma power (210 W), with respect to the lowest power value (60 W), was observed (see Fig. 3). Since the geometry of the gate is a fixed parameter for the measured devices, the similar reduction in both f_T and $f_{\max}$ points out that the power plasma discharge has modified intrinsic characteristics of the heterostructure, likely by changing the surface states in the AlGaN/GaN space region between the gate and the drain/source, which is directly related to the 2DEG density. Moreover, the changes in f_T and $f_{\max}$ are in good agreement with the $I_{DS\max}$ and $g_{m\max}$ values and support that the mobility and charge density in the channel are affected by the plasma pretreatment.

Once established that the low (60 W) power plasma pretreatment showed the best device performance, the time exposure to the plasma was analyzed. However, not significant differences either in dc, pulsed, or RF measurements were observed for 1, 5, 10, and 20 min at the lowest RF power (60 W). These results lead to plasma duration being less critical than plasma power, and therefore, further analysis is basically focused on the effects of plasma power discharge. On the other hand, the different electrical behavior of GaN-based HEMTs as a function of plasma treatment power discharge could partially explain the dispersion from reported studies using the N_2 plasma pretreatment, hence showing the importance of using a low power plasma pretreatment on GaN-based surfaces [9], [12], [16].

B. Surface Characterization

The electric characterization demonstrates that the low power N_2 pretreatment makes more effective the effect of the SiN pasivation layer to mitigate collapse, whereas the use of high power plasma increases this undesirable effect. However, how does the plasma act? The topography and the corresponding surface potential are shown in Fig. 4 for different cases: first, without plasma pretreatment [for bare surface (a–a’) and with the SiN layer (b–b’)] and second, with N_2 plasma pretreatment [at 60 W in (c–c’) and at 210 W in (d–d’), both with the SiN layer]. The root-mean-square roughness obtained by AFM

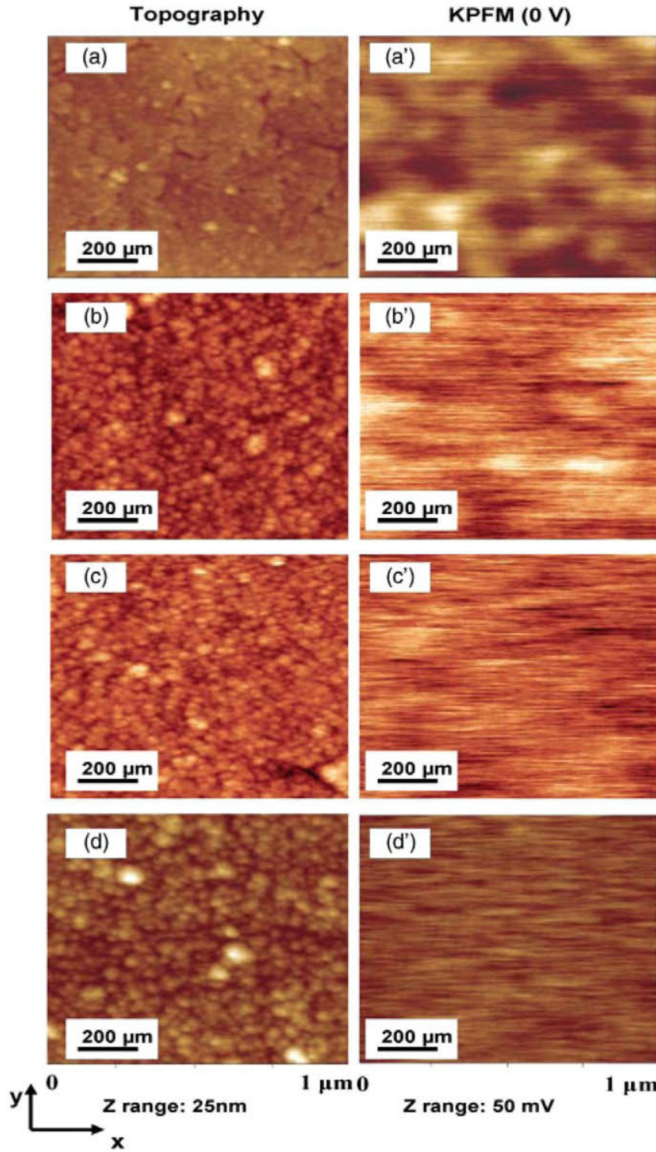

Fig. 4. Topography and surface potential of AlGaN/GaN without any plasma pretreatment: (a–a') without SiN and (b–b') with SiN layer; and with N_2 plasma pretreatment (1 min) at: (c–c') 60 and (d–d') 210 W.

in bare AlGaN and GaN surfaces, regardless of the plasma treatment power, reveals that not significant physical damage on AlGaN and GaN surfaces was introduced by the plasma treatments up to 210 W. However, according to the KPFM images, it is clear that the surface potential is significantly more homogeneous after the plasma pretreatment, with respect to those without any pretreatment. The surface potential inhomogeneity observed in the samples without the plasma pretreatment could be induced by chemical disorder on the AlGaN surface, including the formation of interfacial oxides, and/or by the presence of C, as reported in previous works using X-ray photoelectron spectroscopy [17], [18]. It is noteworthy to mention that this surface potential inhomogeneity is observed for both with and without the SiN layer [see Fig. 4(a') and (b')], showing that the surface potential is more sensitive to the surface treatment than to the SiN layer itself. These results point to the N_2 plasma pretreatment to modify the surface potential and therefore the SiN/AlGaN interface electrical quality.

There are difficulties in extracting accurate surface potential values, particularly due to the humidity level in the atmosphere during the measurement [23]. Nevertheless, qualitative and quantitative trends for surface potential main values were inferred. Although the surface potential shows a homogeneous distribution regardless of the plasma power [see Fig. 4(c') and (d')], the estimated surface potential values follow a different behavior as a function of the plasma power range. For the low power N_2 plasma discharge (60 W), the surface potential (196 $\pm$ 50 mV) was 30% lower than that for the case of no plasma pretreatment (286 $\pm$ 50 mV). In contrast, as the plasma power increases, the surface potential values tend to increase. For instance, the surface potential increased 16% (333 $\pm$ 70 mV) for the high (210 W) power plasma, with respect to the case without any plasma pretreatment. Similar trends were observed in GaN passivated surfaces. These results indicate that the N_2 plasma pretreatment power plays, in fact, a role to control the surface potential, influencing the final AlGaN/SiN interface, and different mechanisms become dominant as a function of the plasma power discharge range.

IV. Model of the N_2 Plasma Power Mechanisms

Taking into account both the AlGaN/SiN surface potential analysis and the HEMT electrical characterization, we propose a possible explanation on how the N_2 plasma power affect the different interface charge densities in the AlGaN/GaN heterostructures. This model is inspired in the results presented by Koley *et al.* [24]. Fig. 5(a) presents a schematic band diagram of an AlGaN/GaN heterostructure without any plasma pretreatment, supposing the Fermi level energy (E_F) close to the conduction band and a surface potential ($\Phi_{\rm sur}$) with a homogeneous surface density state levels. In the absence of electrical bias, neutral charge compensation should govern the AlGaN/GaN heterostructure [25]. The two surface charge densities due to polarization ($+\sigma_{\rm pol}$ and $-\sigma_{\rm pol}$) are compensated as a dipole. In the ideal case, a donor level with a surface charge density ($\sigma_{\rm comp}$) is assumed as origin of the 2DEG charge density ($\sigma_{\rm 2DEG}$) [26]. Besides in a real case, where gate lag is present, a fixed negative trapped charge is also assumed in the surface ($-\sigma_{\rm trap}$), which directly affects the charge in the channel reducing the ideal 2DEG ($-\sigma_{\rm 2DEG} + \sigma_{\rm trap}$).

If the sample is exposed to low plasma power (60 W), active nitrogen radicals in the N_2 plasma are able to react with impurities on the surface (such as carbon [10], [17] and oxygen [18]), and with unstable excess Ga atoms, hence leading to a recovery of surface stoichiometry by reducing the trap surface charges ($\sigma_{\rm trap}$) and lowering the surface potential ($\Phi_{\rm sur}$) [see Fig. 5(b)]. This is also consistent with the decrease in the surface state density between the gate and the drain, responsible for the gate lag reduction, probably by reducing N-vacancies. Therefore, SiN can more effectively passivate the AlGaN surface by using the low power N_2 plasma pretreatment.

On the contrary, if the high power N_2 plasma is applied, surface ion bombardment becomes the dominant mechanism, leading to energetic ions responsible for modifying charge neutrality during the plasma pretreatment. This effect could be explained by an increase in $\Phi_{\rm sur}$ due to the increase in the

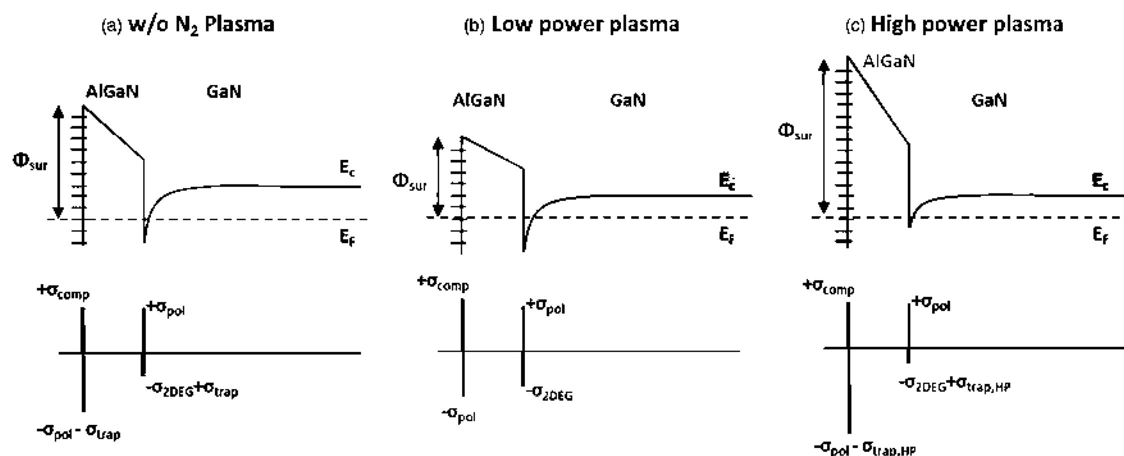

Fig. 5. Schematic band diagram of the AlGaN/GaN heterostructure (a) without any plasma pretreatment and after (b) low and (c) high N_2 plasma power pretreatment. $-\sigma_{\mathrm{trap}}$ represents the trap charges on the surface without any plasma pretreatment, and $-\sigma_{\mathrm{trap,HP}}$ is the trap charge after the high power plasma pretreatment. σ_{pol} represents the fixed polarization charges, and σ_{com} is the compensating charge on the AlGaN surface.

fixed trapped negative charge density ($\sigma_{\mathrm{trap,HP}}$) on the AlGaN surface during the high power plasma exposure [see Fig. 5(c)]. These energetic ions in a N_2 discharge could produce efficient preferential loss of the nitrogen from the near-surface AlGaN region [15], which is in good agreement with the increase in trapping effects and the poor electrical characteristics shown in HEMT devices. Moreover, the increase in the surface potential with the plasma power would lead to moving the Fermi level further away from the conduction band, leading to a decrease in the ideal 2DEG charge density $(-\sigma_{\mathrm{2DEG}} + \sigma_{\mathrm{trap,HP}})$, which is consistent with the electrical results.

V. Conclusion

The effects of power and time of the N_2 plasma pretreatment used in GaN and AlGaN/GaN HEMT heterostructures and devices have been investigated. The low power (60 W) plasma treatment prior to SiN passivation was found to improve the electrical properties of surfaces, independently of the time duration up to 20 min. In contrast, the high power (150 and 210 W) plasma pretreatment showed a degradation of the electronic properties, increasing the sheet resistance of the 2DEG and increasing gate lag effects in HEMTs. Besides, a good correlation between electrical and surface characterization was shown, pointing at the N_2 plasma treatment to induce different mechanisms that control the surface potential and charges as a function of the power discharge.

These results confirm that the GaN-based surface is strongly sensitive to the N_2 plasma power and that the use of a low power (60 W) N_2 plasma surface treatment prior to the passivation results to be a key factor in order to mitigate surface trapping effects in AlGaN/GaN HEMTs, hence helping to reduce one of the bottlenecks to improve their high-frequency performance.

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