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Impact of CF_4 Plasma Treatment on GaN

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***Abstract*—We present a systematic study of the impact of CF_4 plasma treatment on GaN. It was found that CF_4 plasma etches GaN at a slow rate and yields a smooth etched surface. The effect of CF_4 plasma on electrical characteristics of GaN metal–semiconductor field-effect-transistor structures shows that the CF_4 plasma introduces acceptors into the near surface region of the GaN, which depletes mobile electrons. It was further demonstrated that leakage current of AlGaN/GaN (or GaN) Schottky diodes can be significantly suppressed by proper CF_4 plasma treatment. These unique properties of CF_4 plasma can be utilized for the advanced processing of GaN transistors.**

***Index Terms*—CF_4 plasma, electron depletion, etch, GaN, leakage, transistor.**

I. Introduction

FIELD-EFFECT transistors based on GaN and its alloys have shown great promise in high-frequency and high-power applications [1]. Processing technologies for GaN transistors have significantly advanced in the last decade, leading to devices with superior performance. Ohmic-contact resistance has been reduced to $0.12\ \Omega \cdot \mathrm{mm}$ [2]. Cl_2-based plasma etching has been extensively developed, enabling proper isolation and accurate gate recess [3]. SiN_x passivation coupled with field-plate structure boosts the power density up to 40 W/mm at 4 GHz [4]. A combination of gate recess, SiN_x passivation, and deep submicrometer gate technology pushes the device performance to 10 W/mm at 40 GHz [5].

CF_4 plasma has been involved in the processing of GaN transistors, mainly for dry-etching the SiN_x dielectric. It was recently discovered that CF_4 plasma treatment plays an important role in the electrical behavior of GaN transistors. The CF_4 plasma treatment has been demonstrated to shift the threshold voltage of AlGaN/GaN high electron mobility transistors (HEMTs) toward positive bias, thus enabling enhancement-mode operation [6]–[9]. Additionally, it was reported that exposure of AlGaN/GaN HEMTs to CF_4 plasma prior to gate metallization can significantly suppress gate leakage [10]. In this letter, we present a detailed investigation on the effect of CF_4 plasma treatment on GaN transistors. Our results show that the CF_4 plasma treatment has three major effects on GaN. First, the CF_4 plasma treatment etches GaN at a slow rate. Second, it introduces acceptors into GaN, which deplete mobile electrons. Finally, the CF_4 plasma treatment significantly reduces the leakage current of Schottky gates, which can be attributed to the formation of a thin insulating layer on the GaN surface after the CF_4 plasma treatment. Experimental details are described in Section II. The effects of CF_4 plasma treatment are discussed in Section III. Finally, we summarize this letter in Section IV.

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II. Experiments

Metal–organic chemical-vapor-deposition grown GaN or AlGaN/GaN epilayers with an Al content of 22% are employed in this study. A reactive-ion-etch (RIE) system is used for the CF_4 plasma treatment. The CF_4 flow is 20 sccm, the chamber pressure is at 3 mT, and the bias is either 100 or 250 V. Atomic force microscope (AFM) was used to characterize the surface morphology and the etch depth. Scanning transmission electron microscope (STEM) and energy-dispersive X-ray (EDX) analyses were performed to study the structural characteristics of CF_4-treated samples. To study the effect of CF_4 plasma treatment, Schottky diodes and Hall patterns were fabricated on a wafer. Ohmic contacts were made by alloying Ti/Al/Ni/Au, mesa isolation was achieved by Cl_2 RIE etching, and Schottky contacts with the diameter of 180 μm were formed by Ni/Au. Hall measurements using Van der Pauw's method were performed to extract the electron density and mobility of the sample subjected to the CF_4 plasma treatment. With the Schottky diodes, capacitance–voltage (C–V) and current–voltage (I–V) characteristics were measured.

III. Discussion

A. Etching Effect

Initial studies indicated that CF_4 plasma has a minimal etching effect on GaN [6]. This is consistent with the known formation of nonvolatile GaF_3 when the CF_4 plasma reacts with GaN. Our experiments show that with a 250-V plasma bias, CF_4 plasma etches approximately 130 nm of GaN in 90 min, corresponding to an etch rate of around 1.4 nm/min. An AFM scan of the etched region shows that the etched surface is very smooth, with a root-mean-square (rms) roughness of 0.6 nm. When there is no etching or when the plasma exposure time is short, step flow features can be observed. When the etch time is long, e.g., up to 90 min, features of step flow disappear, leaving a smooth etched surface. The disappearance of step flow features can be related to the buildup of a thin surface reaction layer as a consequence of the CF_4 plasma treatment. More information about this thin surface layer will be discussed in the last part of this section.

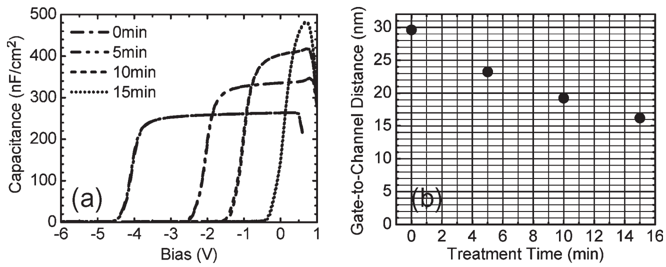

Fig. 1. (a) C–V characteristics of AlGaN/GaN Schottky gate diodes with varied CF_4 plasma treatment times; the dc bias for the plasma treatment is 250 V. (b) Gate-to-channel distance of AlGaN/GaN Schottky gate diodes extracted from C–V.

The smooth etching of GaN by CF_4 plasma provides an alternative means for the gate recess of AlGaN/GaN HEMTs. Gate regions of AlGaN/GaN HEMTs were treated by CF_4 at 250-V plasma bias and varied time prior to gate metallization. The C–V characteristics of AlGaN/GaN Schottky gate diodes with different CF_4 plasma treatment times are shown in Fig. 1(a). From the C–V curves, we can observe that with the CF_4 plasma treatment, the gate-to-channel distance decreases, the electron density drops (as reflected by the integration of capacitance over bias voltage), and a positive threshold voltage shift takes place. With a 15-min treatment, the threshold voltage became positive, thus enabling enhancement-mode devices. The dependence of the gate-to-channel distance on treatment time was extracted from the C–V characteristics and is plotted in Fig. 1(b). We estimate that the CF_4 plasma etches AlGaN at a rate of 1 nm/min. It is noteworthy that an increase of the transconductance can usually be observed for HEMTs subjected to the CF_4 plasma treatment. The similar transconductance increase can also be found in [7]. While Cai *et al.* [7] attributed the increase of the transconductance to the sample nonuniformity, we believe that it is simply due to the etching of the AlGaN in our case.

B. Electron Depletion

The CF_4 plasma treatment can cause depletion of the 2-D electron gas at the AlGaN/GaN interface. The actual cause leading to this electron depletion has been unclear. The electron density in the AlGaN/GaN heterostructure can decrease due to several factors. First, as the CF_4 plasma etches AlGaN, the electron density can decrease simply due to a thinner AlGaN layer. Second, CF_4 plasma can modify the AlGaN surface and increase the surface barrier so that more electrons are depleted. Third, the CF_4 plasma treatment can introduce acceptors into the AlGaN/GaN structure, reducing the electron density.

To clarify the actual cause of electron depletion in the CF_4 plasma treated AlGaN/GaN structures, we characterized the influence of CF_4 plasma treatment on mobile electrons in a simpler structure, which is the metal–semiconductor field-effect transistor (MESFET). Prior to gate metallization, the gate regions were treated with CF_4 plasma. The treatment time was varied from 5 to 25 min, and the bias was kept at 250 V. The electron density and mobility extracted from room temperature Hall measurements are shown in Fig. 2. The electron density monotonically decreased with an increasing treatment time; at

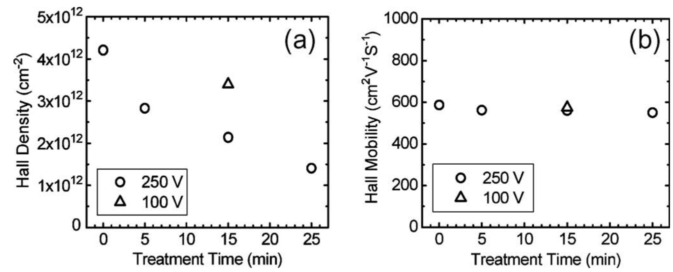

Fig. 2. Room temperature (a) Hall density and (b) mobility of GaN MESFET structures under different CF_4 plasma treatment times and bias conditions.

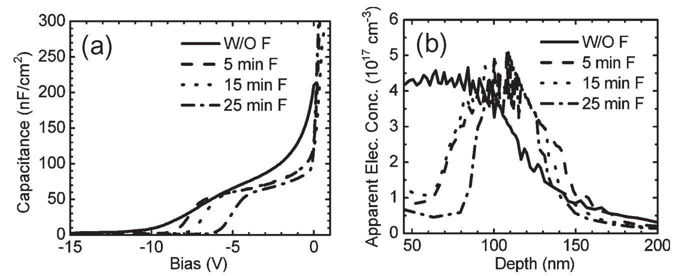

Fig. 3. (a) C–V characteristics of GaN Schottky gate diodes with varied CF_4 plasma treatment times; the dc bias for the plasma treatment is 250 V. (b) Apparent electron concentration profile in GaN Schottky gate diodes extracted from C–V.

lower plasma bias, there was a smaller decrease in electron density. The electron mobility was nearly unaffected by the CF_4 plasma, regardless of treatment time and plasma bias.

The C–V characteristics of this MESFET structure sample are shown in Fig. 3(a). From these C–V characteristics, the apparent electron concentration profile can be extracted using a method introduced in [11]. As shown in Fig. 3(b), electrons in the near surface region were depleted after the CF_4 plasma treatment. Longer treatment time leads to more electron depletion. Since the etch rate is too slow to account for the large loss of electron density, etching is not the dominant factor leading to the reduction of electron density. According to electrostatic analysis with Poisson's equation, the surface barrier height has to be greater than 4 eV to have a depletion width of 100 nm if there are no acceptors or acceptor-type defects introduced into the GaN. Since the band gap of GaN is 3.4 eV, a 4-eV barrier height is implausible. Therefore, acceptors introduced by CF_4 plasma should be responsible for the electron depletion. The nature of these CF_4-induced acceptors requires more detailed study.

C. Leakage Reduction

Leakage current of Schottky gates on GaN and AlGaN/GaN heterostructures can be significantly reduced by exposing the gate region to CF_4 plasma prior to Schottky gate metallization. In view of the great interest in gate leakage reduction for HEMTs, we chose to delineate the effect of a CF_4 plasma treatment on leakage current of AlGaN/GaN Schottky diodes. The effect on GaN Schottky diodes is similar. The I–V characteristics of the Schottky diodes with different CF_4 plasma treatment times are shown in Fig. 4(a). The leakage current continuously decreases with an increasing treatment time. With

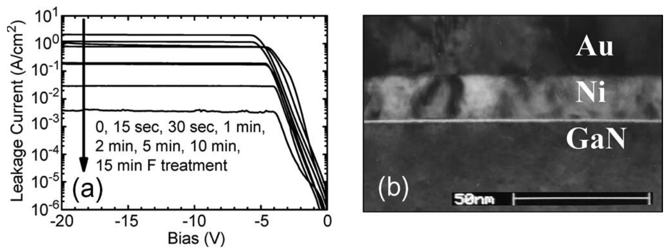

Fig. 4. (a) Reverse leakage characteristics of AlGaN/GaN Schottky gate diodes with varied CF_4 plasma treatment times; the dc bias for the plasma treatment is 100 V. (b) Cross-sectional TEM image of a GaN-Ni/Au Schottky diode with CF_4 plasma treatment prior to Schottky metal evaporation.

a 15-min treatment, the reverse leakage current drops by nearly three orders of magnitude. A BCl_3/Cl_2 shallow etch following the CF_4 treatment increased the leakage current to a level that is similar to that without the CF_4 plasma treatment, suggesting that a surface effect rather than a bulk effect played a critical role in leakage current reduction.

The CF_4 plasma may react with GaN (or AlGaN) to form nonvolatile F-containing compounds. This surface reaction may form an insulating surface layer that blocks leakage current. Fig. 4(b) shows the STEM image of the structure across the interface between Schottky metal and GaN, which was treated with CF_4 plasma at 250 V for 25 min. A very smooth, uniform, and thin interlayer could be observed between the Schottky metal and the GaN with an abrupt interface. An unambiguous signal corresponding to the element F was detected from the thin interfacial layer by an EDX measurement, suggesting that the thin layer contains F. This thin layer was not found in a control sample without the CF_4 plasma treatment. Buildup of this layer covered the GaN surface, so that the typically observed step flow features of as-grown GaN could not be observed for GaN after prolonged CF_4 plasma treatment. This is consistent with the AFM observation. The formation of this thin surface layer is a dynamic process, i.e., CF_4 plasma forms a thin layer on the surface, etches it away, and forms it again. More detailed study is required to completely understand the correlation between the thin interfacial layer and the leakage reduction.

IV. Conclusion

In conclusion, we studied the impact of CF_4 plasma treatment on GaN. Slow and smooth etching effect was observed. The introduction of acceptors into GaN (or AlGaN/GaN) was deduced to be the major cause of electron depletion by the CF_4 plasma treatment. Schottky gate leakage can be effectively reduced by the CF_4 plasma treatment. The leakage reduction effect is related to the formation of an F-containing surface layer. These effects, which are associated with the CF_4 plasma treatment, can be deployed for advanced processing of GaN-based transistors, such as fabricating enhancement-mode HEMTs and HEMTs with low gate leakage.

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