Influence of Atomic Hydrogen Treatment on the Threshold Voltage of p-Gate High Voltage GaN Transistors

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Abstract

AlGaN/GaN HEMT is one of attractive candidates for next generation high power devices because of high carrier mobility in 2DEG channels and high breakdown voltage due high critical electric field. In order to apply the AlGaN/GaN HEMTs for power switching applications the normally off operation is required. Enhancement type behavior of GaN HEMT transistors is obtained by using p-type Mg-doped GaN gate structures. The optimized epitaxial designs enable threshold voltage close to +2V. In present work, it is shown that atomic hydrogen treatment of the Mg doped p-GaN before gate metal evaporation can increase the threshold voltage up to +3.5V. It can be caused by the hydrogen-induced dipole layer formation at the p-GaN semiconductor interface after atomic hydrogen treatment. Further increase of treatment time lead to reduce the threshold voltage by form neutral complexes. Neutral complexes reduce the Mg doping level of p-GaN layer. There was no visible parameters degradation after thermal annealing at T = 300 ^oC for t = 30 min in vacuum environment. It can be caused by the formation thermally stable hydrogen-induced dipole layer at the p-GaN interface after the atomic hydrogen treatment.

INTRODUCTION

To break through the material limits of Silicon and to realize the drastic performance improvement needed to meet the severe requirements of power electronics in the future, wide band gap semiconductors such SiC and GaN have attracted much attention. AlGaN/GaN HEMTs are generally promising candidates for switching power transistors due to their high breakdown strength and the high current density in the transistor channel giving a low on-resistance [1,2]. The normally-off GaN high-mobility 2DEG transistor is required for applications in power electronics [3]. Enhancement type behavior of GaN power transistors is obtained by using p-type GaN gate structures. Mg-doped GaN layer placed on the top of AlGaN/GaN hetero structures with an epitaxial design similar to standard normally-on GaN devices is shifts the conduction band in the 2DEG region above the Fermi level, leading to a completely depleted 2DEG. If p-GaN layer is laterally confined to the gate region only, the devices are inherently normally-off and can only be turned on by applying a positive gate bias. The threshold voltage for current turn-on depends on epitaxial layer design, p-doping concentration and abruptness of p-doping. Typically, threshold values between +1V and +1.5V are obtained, optimized epitaxial designs even enable threshold voltage close to +2V. However, the required Vth > +1V is often achieved by a low Al-concentration in the AlGaN barrier, giving a reduced electron density in the 2DEG of the transistor channel. But p-GaN/AlGaN/GaN HEMTs with the lower Al-concentration in AlGaN barrier have the higher on-resistance. So there is a need for finding new methods to increase the threshold voltage of GaN transistors with high Al-concentration in AlGaN barrier.

It is known that grown by molecular beam epitaxy grown of the Mg-doped GaN exhibits p-type conductivity in the as-grown state [4]. Nakamura and co-wokers [5] found that hydrogen treatment of p-GaN by MOCVD can be responsible for the semi-insulating nature of the material. They observed that thermal annealing of p-type GaN:Mg at temperature above 600 ^oC in NH_3 atmosphere decreased the conductivity by six orders of magnitude, whereas a similar anneal in a N_2 ambient left the conductivity unchanged. From first-principles total-energy calculations, Neugebauer and Van de Walle [6] have found that isolated hydrogen should be an interstitial donor in GaN : Mg under MOCVD growth conditions and is, therefore, able to compensate deliberately incorporated Mg acceptors. They have also found that hydrogen can form a stable complex with Mg.

The aim of present work is to investigate the influence of the atomic hydrogen treatment of the Mg doped p-GaN on the threshold voltage and electrical performance of p-GaN/AlGaN/GaN high voltage transistors and diodes.

EXPERIMENTAL

The p-GaN/AlGaN/GaN epitaxial structures produced by MOCVD on silicon substrates were used in experiments. The top p-GaN epitaxial layers were doped with Mg during growth. The films were 50 nm thick and doping

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concentration of Mg atoms incorporated was determined with secondary ion mass spectrometry to 2 x 10^{19} cm^{-3}. The total thickness of the nitride buffer layer is about 4 µm. The Al mole fraction of AlGaN barrier layer was 25% to reduce on-resistance. The p-type gate is formed by the selective etching of GaN/AlGaN. After the formation of device isolation area, the ohmic contacts based on Ti/Al/Mo/Au and Pd gate metals are formed. Prior to the gate metal e-beam evaporation samples were treated *in-situ* by the atomic hydrogen (AH) with flow density of about $j > 10^{16}$ at cm^{-2} s^{-1} during t = 10 – 60 s at room temperature. The DC parameters of the fabricated GaN transistors and diodes were measured by HP4156A Semiconductor Parameter Analyzer.

RESULTS

Fig. 1 and 2 show the schematic and microscopic images of fabricated 10 mm p-gate GaN-on-Si transistor. The gate length definited by the p-GaN width is 1.8 µm and distance between the source and drain is 7.5 µm.

The fabricated p-GaN/AlGaN/GaN transistor with untreated p-GaN layer and $Al_{0.25}Ga_{0.75}N$ barrier demonstrates the normally-on operation with the threshold voltage is about Vth = -1.4V. The specific on-resistance is 2.4 mOhm x cm^2 and off-state breakdown voltage is 250V.

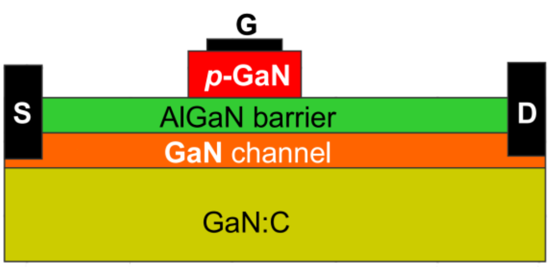

Fig. 1. Schematic image of p-GaN/AlGaN/GaN/Si transistor

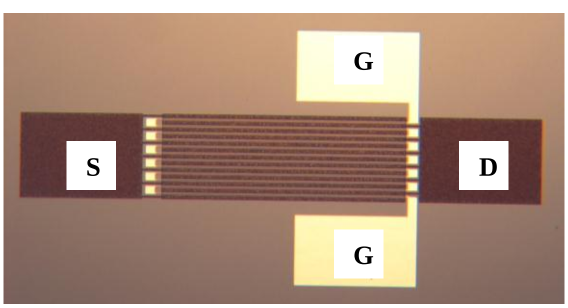

Fig. 2. Microscopic image of 10 mm p-GaN/AlGaN/GaN/Si transistor

Fig. 3 shows the threshold voltage of p-GaN/AlGaN/GaN transistors as a function of the treated time in the atomic hydrogen flow. It can be seen that the *in-situ* atomic hydrogen treatment of p-GaN layers can increase the threshold voltage of transistors. There is a Vth = +3.5V observed after AH treatment during t = 10 s. Further increase of treatment time from t = 10 to 60 s lead to reduced the threshold voltage value from Vth = +3.5 to +2V.

After the atomic hydrogen treatment of p-GaN surface for t = 10 s the hydrogen-induced dipole layer at the semiconductor interface is formed. The dipole layer is responsible for the work function change and the threshold voltage shift of the device. Further increase of treatment time lead to penetrate the atomic hydrogen into p-GaN layer. It is known [6,7] that atomic hydrogen whose diffusivity is large form neutral complexes with dopant atoms or combine with dangling bonds. Neutral complexes reduce the Mg doping level of p-GaN layer. So the further reduce of threshold voltage of p-GaN transistors can be observed.

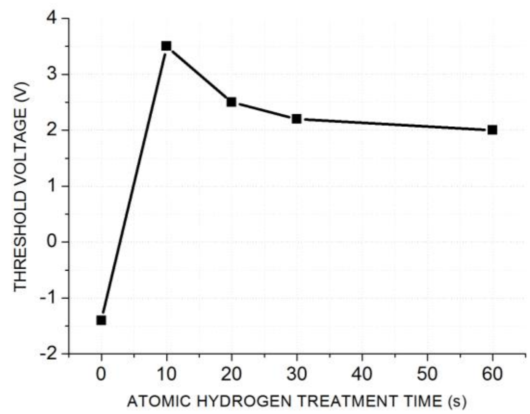

Fig. 3. Threshold voltage of p-GaN/AlGaN/GaN/Si transistors as a function of the treated time in the atomic hydrogen flow.

Fig. 4 shows the output characteristics of 10 mm p-GaN/AlGaN/GaN/Si transistors fabricated with atomic hydrogen treatment during t = 10 s. The fabricated normally-off p-gate atomic hydrogen treated GaN transistors demonstrate the similar electrical performance as the untreated one.

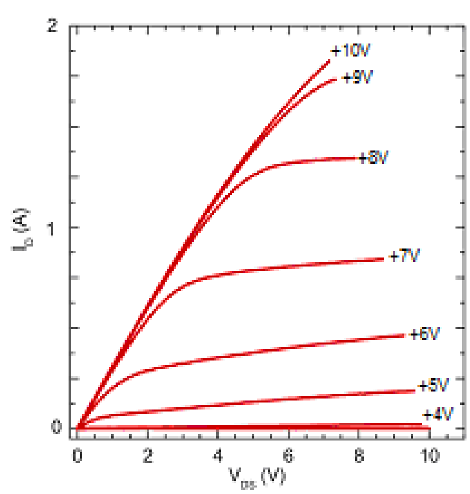

Fig. 4. Output characteristics of 10 mm p-GaN/AlGaN/GaN/Si transistors fabricated with atomic hydrogen treatment during t = 10 s

The microscopic image of fabricated p-GaN/AlGaN/GaN/Si diode is shown at fig. 5. The diode diameter is 400 μm.

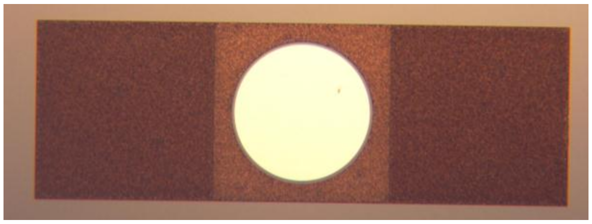

Fig. 5. Microscopic image of p-GaN/AlGaN/GaN/Si diode

Fig. 6 shows the forward current-voltage characteristics of p-GaN/AlGaN/GaN/Si diodes: untreated (1) and treated in the atomic hydrogen flow during t = 10 s (2), t = 20 s (3), t = 30 s (4), t = 60 s (5) at room temperature. It can be seen that the atomic hydrogen treatment can increase the barrier height of Pd/p-GaN structure. Theese results correlate with increasence of threshold voltage of p-gate GaN transistors after atomic hydrogen treatment (fig. 3).

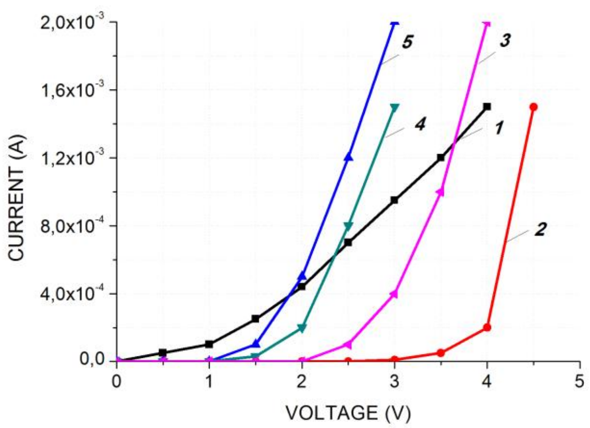

Fig. 6. Forward current-voltage characteristics of p-GaN/AlGaN/GaN/Si diodes: untreated (1) and treated in the atomic hydrogen flow during t = 10 S (2), t = 20 s (3), t = 30 s (4), t = 60 s (5) at room temperature

There was no visible degradation of transistor and diode parameter after thermal annealing at T = 300 ^{o}C for t = 30 min in vacuum environment. Thermal stability of parameters observed can be explained by the formation of thermally stable hydrogen-induced dipole layer at the p-GaN interface after the atomic hydrogen treatment.

Conclusions

High voltage enhanced mode GaN transistor is a basic element for power electronics applications. For achieving normally-off operation p-type Mg-doped GaN gate structures are used. The optimized epitaxial designs enable threshold voltage close to +2V.

In present work, it was shown that atomic hydrogen treatment of the Mg doped p-GaN before gate metal evaporation can improve the threshold voltage of transistor. The threshold voltage value is about +3.5V can be achieved after treatment during t = 10 s. It can be caused by the hydrogen-induced dipole layer formation at the p-GaN semiconductor interface after atomic hydrogen treatment.

There was no visible parameters degradation after thermal annealing at T = 300 ^{o}C for t = 30 min in vacuum environment. It can be caused by the formation thermally stable hydrogen-induced dipole layer at the p-GaN interface after the atomic hydrogen treatment.

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