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

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To break through the material limits of Silicon and to realize the drastic performance improvement needed to meet the severe requirements 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 according Fig. 1. Mg-doped GaN layer placed on the top of GaN/AlGaN hetero structures with an epitaxial design similar to standard normally-on GaN devices is shifting 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 (Fig. 1), 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 dencity 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 the finding of new methods to increase the threshold voltage of GaN transistors with high Al-concentration in AlGaN barrier are actually task today.

It is known that grown by molecular beam epitaxy of the Mg-doped GaN exhibits p-type conductivity in the as-grown state [4]. Nakamura and co-wokers [5] founded that hydrogen treatment of p-GaN by MOCVD can responsible for the semi-insulating nature of the material. They observed that thermal annealing of p-type GaN:Mg at temperature above 600 ^{o}C 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.

The p-GaN/AlGaN/GaN epitaxial structures produced by MOCVD on sapphire substrates were used in experiments. The top p-GaN epitaxial layers were doped with Mg during growth. The films were 100 nm thick and doping concentration of Mg atoms incorporated was determined with secondary ion mass spectrometry to by 2 x 10^{19} cm^{-3}. The total thickness of the nitride buffer layer is about 3 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 = 7 x 10^{16} at cm^{-2} s^{-1} during t = 10 – 60 s at room temperature. The DC parameters of the fabricated GaN transistors were measured by HP4156A Semiconductor Parameter Analyzer.

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 gate length definited by the p-GaN width is 2 µm and distance between the source and drain is 7.5 µm. The specific on-resistance is 2.4 mOhm x cm^2 and off-state breakdown voltage is 250V.

Fig. 2 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 = +3V observed after AH treatment during t = 30 s. It has been shown that isolated hydrogen acts as a donor in p-type GaN and is highly mobile [6,7]. During the hydrogenation process, the hydrogen atoms are likely either to evolve out of the sample or are immobilized at internal sites where they cease to influence the p-type conductivity.

The fabricated normally-off p-gate atomic hydrogen treated GaN transistors demonstrate the similar electrical performance as the untreated one. And there are no visible parameters degradation after thermal annealing at T = 300 ^{o}C during t = 30 min in vacuum environment. It can be caused by the formation thermally stable Mg-H complexes in the p-GaN layer after hydrogenation.

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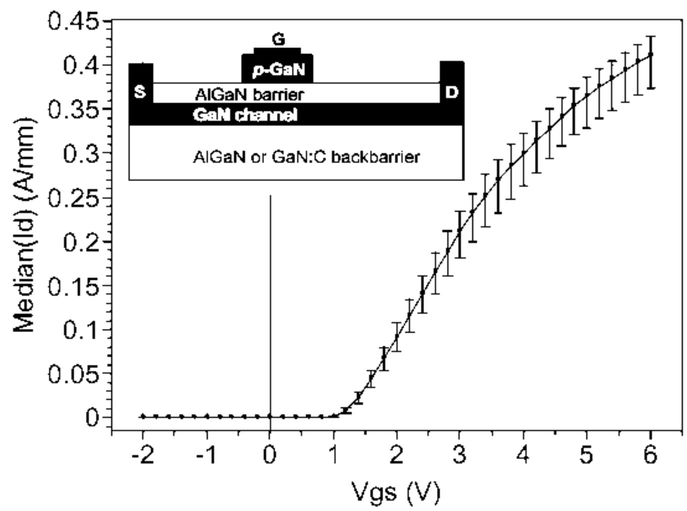

Fig.1. Transfer characteristics of p-GaN gated normally-off GaN transistors.
Inslet: Schematics of a normally-off transistor in p-GaN gate technology.

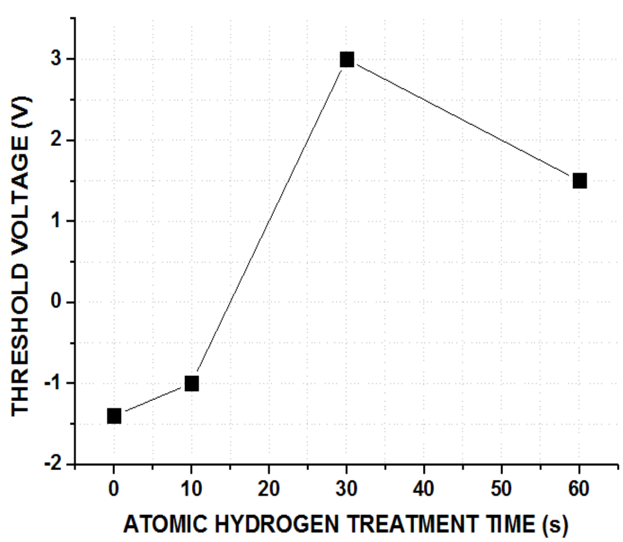

Fig. 2. Threshold voltage of p-GaN/AlGaN/GaN transistors as a function of the treated time in the atomic hydrogen flow.