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Deformation of the AlGaN/GaN metal-oxide-semiconductor heterostructure field-effect transistor characteristics by UV irradiation

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Abstract

The impact of UV irradiation process on the AlGaN/GaN metal-oxide-semiconductor heterostructure field-effect transistor was investigated. Due to the high intensity UV irradiation before the gate dielectric deposition, the conductivity of AlGaN/GaN structure and the drain saturation current of the transistor increased by about 10 %. However, the pinch off characteristics of transistor was severely deformed by the process. By comparing the electrical characteristics of the transistors, it was proposed that the high intensity UV irradiation formed a sub-channel under the two dimensional electron gas of AlGaN/GaN structure even without additional impurity injection.

Key words: AlGaN/GaN, MOSHFET, UV, 2-DEG, Deformation

I. Introduction

AlGaN/GaN high electron mobility transistors (HEMTs) and metal-insulator-semiconductor heterostructure field-effect transistors (MISHFETs) are suitable for high power and high frequency operation, especially in harsh environments, due to its inherent material property.[1-3] However, studies for better and reliable electrical characteristics of the devices have continued up to date, because there are needs for high voltage, low leakage current, less degradation in pulsed operation, etc.[4, 5] The electrical characteristics of AlGaN/GaN based transistors are very sensitive to the surface, because conductive channels with high carrier density form without any dopant injection, and lots of traps exist on the surface. Surface traps act as leakage current paths, and decrease the breakdown voltage. Also, charged traps can modify the channel, and be operated as a virtual gate. Moreover, traps capture and release charges with time delay, thereby degrading the frequency dependent characteristics of the HEMT, as in many reports.[6, 7] Process related physical damage and chemical reaction have been considered as reasons for generation of surface traps. The ionic bombardment at the plasma process induces damage, and leaves traps behind the surface, because the surface is exposed to chemicals and ions during the process.[8] To reduce traps and their effects, surface passivation using SiN_x, SiO_2, and Al_2O_3 has been proposed and examined. Also, surface treatments with either chemicals or plasma were investigated, to cure the surface for improved electrical characteristics.[9, 10] There is another possible source that degrades the surface.: the UV energy, of which the wave length is less than 365 nm, is higher than the bandgap energy of GaN. When GaN surface is irradiated by UV shorter than

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the wave length, Ga atoms are excited to an active state, and easily changed their state to generate carriers. Also, there is a possibility to make traps. During the optical lithography, UV is irradiated to the photoresist, and some of the energy is delivered to the surface, despite the masking of photoresist. Further, the surface can be exposed to UV during the plasma process, such as substrate etching and dielectric deposition, because UV generation is possible at the plasma. The lithography and the plasma processes are repeated many times for device fabrication, and the accumulation of exposure can make the surface change from the beginning, although the effect is small at each process. This can degrade the surface and channel properties, and thereby the electrical characteristics of the transistor. However, there was no report of the UV irradiation effect on the device characteristics, although the process is always done in the fabrication. Most of the reports have studied the effect of UV response on the fabricated device, by measuring the electrical characteristics under, or after, UV illumination.[11]

In this study, the effect of UV irradiation process on the electric characteristics of an AlGaN/GaN metal-oxide-semiconductor heterostructure field effect transistor (MOSHFET) was investigated, by irradiating the surface with high intensity UV, before the gate dielectric deposition. We report that the UV severely deformed the electrical characteristics of AlGaN/GaN MOSHFET, by introducing a sub-channel under the two-dimensional electron gas (2-DEG).

II. Experiment

To investigate the UV radiation effect, AlGaN/GaN MOSHFETs were fabricated, using an Al0.25 Ga0.75 N/GaN structure with a 3 nm GaN cap layer. The AlGaN/GaN structure was prepared by the sequential growth of 30 nm AlGaN layers over a GaN buffer layer, by metal organic chemical vapor deposition, on a 4-H SiC substrate. The AlGaN/GaN structure was etched by dry etching technique, to define an isolated active region of the transistor. Source and drain ohmic contacts were formed on the active region by deposition of Ti/Al/Ni/Au metals, and 30 seconds annealing at a temperature of 900 °C in N_2 ambient. After that, gate dielectric of SiO_2 was deposited with 15 nm thickness on the surface of two samples, by the plasma enhanced chemical deposition (PECVD) process. Just before the deposition, one of the samples was UV irradiated, and the other was not, for the comparison, as shown in figure 1. UV irradiation was performed on one of the samples, using a 150 W deuterium lamp by the energy 150 mJ/cm^2. Most of the energy of the lamp is distributed below 360 nm, which is higher energy than the band gap of GaN. After irradiation, The UV irradiation and SiO_2 deposition processes were performed continuously in the same chamber to minimize surface variation and the temperature was 250 °C. Ni/Au gate metals were deposited on SiO_2 between the source and drain ohmic contact, and SiO_2 on the source and drain ohmic contacts were selectively etched.

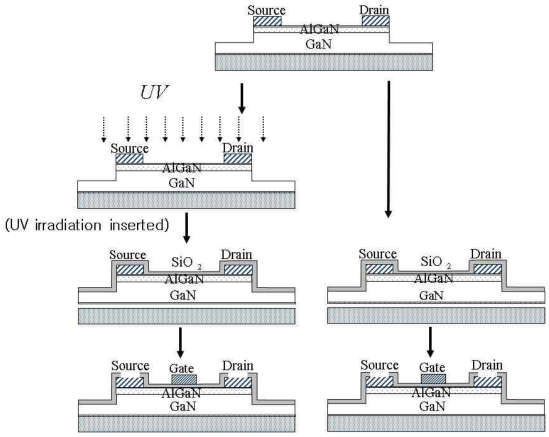


Fig. 1. Fabrication of AlGaN/GaN MOSHFET: (a) The UV irradiation was performed on one sample before SiO2 deposition, and (b) the other was not irradiated.

III. Results and Discussion

Fig. 2 shows the leakage current characteristics between the two isolated pads, with a same width and distance of 100 μm. Although the 2-DEG was removed by the etching of AlGaN, leakage current of the order of 10^{-7} A flowed between the two pads. The leakage current was decreased to less than 10^{-8} A after SiO_2 deposition. Because all the process was performed at the same condition, except for the UV irradiation 250 °C, it is thought that the leakage current lowering came from the surface modification due to the SiO_2 deposition, as in other reports.19, 20 The UV process had little effect on the isolation leakage current variation. However, there was a difference in the channel resistance of AlGaN/GaN structures, between the UV irradiated and non-irradiated sample. The sheet resistances of the channel determined by the transfer length method were similar as 535 Ω/sq. before and after SiO_2 deposition, as shown in figure 3. But it was decreased to 503 Ω/sq. for the UV irradiated sample. Since the sheet resistance distributed within the variation of 9 Ω/sq. for examined sample, it was regarded that UV induced a decrease of the sheet resistance.

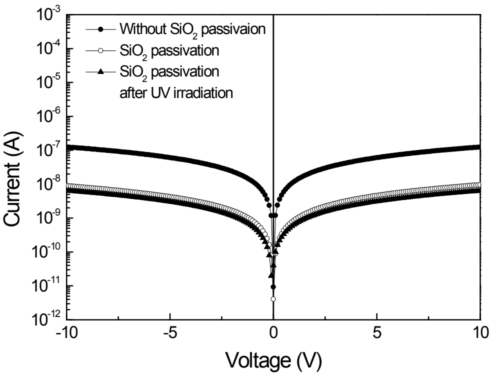


Fig. 2. Leakage current characteristics between two isolated pads.

In addition, UV irradiation seriously modified the electrical characteristics of MOSHFET. Fig. 4 shows the transconductance and drain current characteristics on gate voltage at drain source voltage of 5 V for the two MOSHFETs, with gate length and width of 1 μm and 50 μm, respectively. The drain current of MOSHFET was 33.2 mA at 0 V of gate voltage at the sample without UV irradiation. But the current was increased to 36.8 mA by UV irradiation, which is 10% higher for UV irradiated sample.

Moreover, there was a marked difference in the transconductance curve. Although the transconductance curve was typical for the transistor of a sample without UV process, it has a tail below -4 V of gate voltage for the UV irradiated sample. These variations were shown for all transistors of the sample, though there is a little difference in the amount of the variation. Since the transconductance of AlGaN/GaN MOSHFET increases rapidly at the threshold voltage due to the two-dimensional carrier distribution, the tail from -4 V to -8 V of figure 4 indicated that the 2-DEG channel of AlGaN/GaN structure was modified to have sub-channel under 2-DEG by UV process.

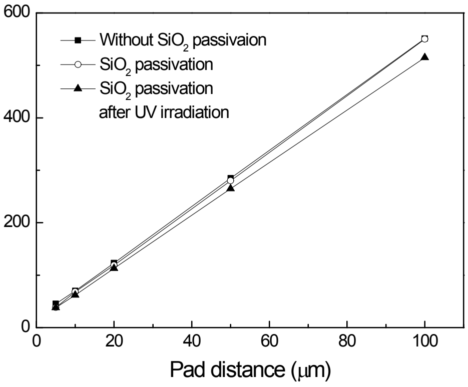


Fig. 3. resistance between the pads on the AlGaN/GaN channel corresponding to the pad distance.

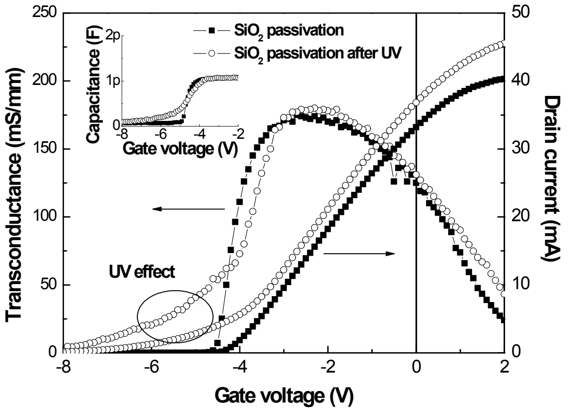
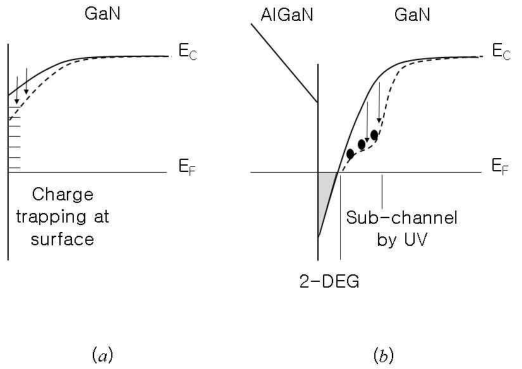


Fig. 4. Transconductance, drain current, and capacitance characteristics corresponding to the gate voltage of AlGaN/GaN MOSHFET.

The sub-channel needs larger negative voltage for modulation than the 2-DEG because it is located under the 2-DEG. The sub-channel seemed to contribute to the increase of drain current and the decrease of sheet resistance in figure 3. However, the formation of sub-channel is not possible at room temperature without any dopant. Also, the dissociation of GaN is not easy because the dissociation energy is very high as 206 kcal/mole for GaN.21 But, GaN can be excited by UV irradiation and the excitation reduced the dissociation energy. In our case, bond breaking seemed to be happened at the process temperature of 250 °C under UV irradiation and some of the broken bond seemed to be left a broken state, because there was no remarkable variation of the electrical characteristics for a transistor with UV irradiation at room temperature. When UV is irradiated on the GaN surface, where the AlGaN layer is etched out, Ga atoms are excited and there is an opportunity to break the bonding of GaN. The broken bonding forms faults, nitrogen and Ga vacancies in GaN and the nitrogen vacancies can act as donors in GaN. But, the donors did not contribute to current conduction because they were depleted by the surface states as in figure 5(a).



(a) (b)

Fig. 5. Band diagrams of AlGaN/GaN and GaN after the UV irradiation process.

As like nitrogen vacancies, Ga vacancies can be acceptor, but the possibility is much lower than nitrogen vacancies. On the contrary, donors of GaN generated by UV irradiation revealed different results in AlGaN/GaN, due to its layered structure. The difference in band-gap energy between AlGaN and GaN forms a quantum well at the interface, and the energy barrier toward AlGaN prevents electrons from moving to AlGaN. The confined electrons act as a carrier with high electron mobility. In a similar way, the electrons on donors generated by UV in GaN cannot move to AlGaN, due to its barrier, in contrast with the case without AlGaN, where the carrier can contribute to current conduction. The electrons on donors in GaN have lower mobility than the confined electrons, and are spatially distributed corresponding to the UV penetration, like a low mobility sub channel formed under 2-DEG. The carrier distribution under 2-DEG was confirmed by CV measurement results of the gate electrodes. As shown in the inset of figure 4, the two samples have different capacitance profiles. The steep capacitance profile of the MOSHFET without UV irradiation revealed two- dimensional carrier distribution in AlGaN/GaN structure because carrier density can be estimated by the integration of capacitance over gate voltage. But, the capacitance distributed widely at gate voltage of the MOSHFET with UV irradiation process. It indicated the existence of carriers below 2-DEG. From the above results, it was confirmed that carriers are generated under 2-DEG by the high intensity UV irradiation on the AlGaN/GaN surface even without impurity injection and thermal treatment, and the carriers modify the channel properties, to degrade the pinch off characteristics of MOSFET. During the MOSHFET and HEMT fabrication processes using AlGaN/GaN structure, the AlGaN/GaN surface is exposed many times to UV by lithographic process using UV source or plasma processes emitting UV. Since the UV exposed surface has the possibility of changing the 2-DEG channel, notwithstanding that the impact is not as much as in our experiment, its impact on the device characteristics has to be considered.

III. Conclusion

As a conclusion, it was found that by comparing the electrical characteristics of the AlGaN/GaN MOSHFETs, the high intensity UV irradiation before the gate dielectric deposition formed a sub-channel under the 2-DEG of AlGaN/GaN structure even without additional impurity injection. The AlGaN barrier seemed to prevent from moving carriers generated by donors that resulted from the broken bond of GaN by high energy UV irradiation and the donor formed sub-channel with lesser electrical properties than 2-DEG. The sub-channel provided an improved conductivity of the AlGaN/GaN channel, and drain current increase of the MOSHFET by about 10%. But, the pinch-off characteristics of MOSHFET were severely deformed by the sub-channel.

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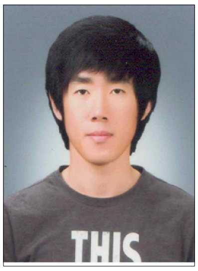

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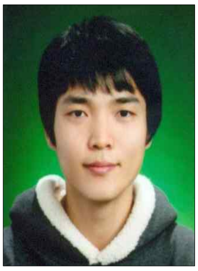

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