JOURNAL OF SEMICONDUCTOR TECHNOLOGY AND SCIENCE, VOL.13, NO.6, DECEMBER, 2013 http://dx.doi.org/10.5573/JSTS.2013.13.6.617

Effect of electron-beam irradiation on leakage current of AlGaN/GaN HEMTs on sapphire

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Abstract—**This study examined the effect of electron-beam (E-beam) irradiation on the electrical properties of n-GaN, AlGaN and AlGN/GaN structures on sapphire substrates. E-beam irradiation resulted in a significant decrease in the gate leakage current of the n-GaN, AlGaN and HEMT structure from 4.0×10^{-4} A, 6.5×10^{-5} A, 2.7×10^{-8} A to 7.7×10^{-5} A, 7.7×10^{-6} A, 4.7×10^{-9} A, respectively, at a drain voltage of -10V. Furthermore, we also investigated the effect of E-beam irradiation on the AlGaN surface in AlGaN/GaN heterostructure high electron mobility transistors(HEMTs). The results showed that the maximum drain current density of the AlGaN/GaN HEMTs with E-beam irradiation was greatly improved, when compared to that of the AlGaN/GaN HEMTs without E-beam irradiation. These results strongly suggest that E-beam irradiation is a promising method to reduce leakage current of AlGaN/GaN HEMTs on sapphire through the neutralization the trap.**

Index Terms—**AlGaN/GaN HEMTs on sapphire, gate leakage current, E-beam irradiation, surface state**

I. INTRODUCTION

Power semiconductor switching devices with breakdown voltages of several hundred volts have been examined to reduce the power loss for switching mode power supplies and inverter systems [1]. AlGaN/GaN based HEMTs have been widely studied for the application of the power semiconductor devices due to their excellent high field electron transport properties and high-breakdown electric field [2]. However, the device performance and reliability of conventional AlGaN/GaN HEMTs have been significantly limited due to a high gate leakage current [3].

The high surface leakage currents in AlGaN/GaN HEMTs can be attributed to gallium vacancies (V_{Ga}) [4, 5], nitrogen vacancies (V_N) [6, 7] and impurities such as carbon, hydrogen and oxygen into the crystal [8, 9]. Furthermore, Kotani *et al.* reported that high-density of V_N and oxygen impurities play a more important role in AlGaN Schottky diodes [10]. In this study, in order to reduce leakage current of the AlGaN/GaN HEMTs, we have investigated the effect of E-beam irradiation on the electrical properties of n-GaN, AlGaN and AlGN/GaN structures as well as AlGaN/GaN HEMTs on sapphire substrates. The results will show that the E-beam irradiation can greatly decrease in the leakage current due to neutralization of vacancies in surface of GaN or AlGaN layer.

II. EXPERIMENTAL

The transistors using n-GaN or AlGaN as well as AlGaN/GaN HEMTs were fabricated to determine the effect of E-beam irradiation on the electrical properties of the transistor (Fig. 1). For fabrication of AlGaN/GaN HEMTs, we performed MESA-isolation etching with a height of 200 nm using Cl_2/BCl_3 inductive coupling plasma (ICP). Ohmic contact was, then, prepared by electron beam evaporation of Ti/Al/Ni/Au layers with

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Manuscript received Apr. 30, 2012; accepted Oct. 7, 2013

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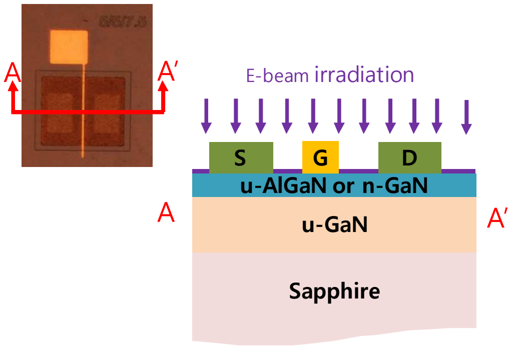

Fig. 1. Schematic diagram of the AlGaN/GaN HEMTs.

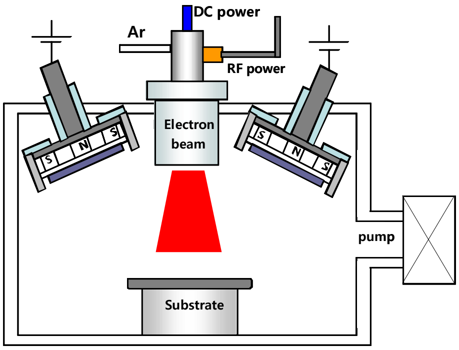

Fig. 2. Electron-beam irradiation system.

conventional lift-off method, followed by rapid thermal-annealing at 800 °C for 60 s in a N_2 ambient. Finally, the Ni/Pt/Au gate metal was produced by an electron beam evaporator. The gate length and gate width were 5 and 200 μm, respectively. And source-to-gate and gate-to-drain spacing of the HEMT devices were 5 and 10 μm, respectively.

After the fabrication of transistors, as shown in Fig. 2, E-beam was irradiated on the device surface with a RF power of 150 W and different DC voltages for 1 min. The Ar flow rate and working pressure in the E-beam irradiation system was 15 sccm and 5×10^{-4} Torr, respectively. The gate leakage current, output and transfer characteristics were measured using a HP4145B parameter analyzer.

III. Results and Discussion

Fig. 3 shows the reverse Schottky gate current characteristics of the three types of transistor devices (a) n-GaN (b) AlGaN (C) AlGaN/GaN hetro-structure, as function of the E-beam irradiation power on the source-to-gate and gate-to-drain spacing region. The gate leakage current decreased with increasing in E-beam irradiation power, as shown in Fig. 3. The reverse leakage current of u-AlGaN/u-GaN sample was several orders of magnitude higher than the HEMT sample. This fact seems to be appearing because of different AlGaN layer thickness(u-AlGaN/u-GaN: AlGaN barrier 1μm, HEMT : AlGaN barrier 25 nm).

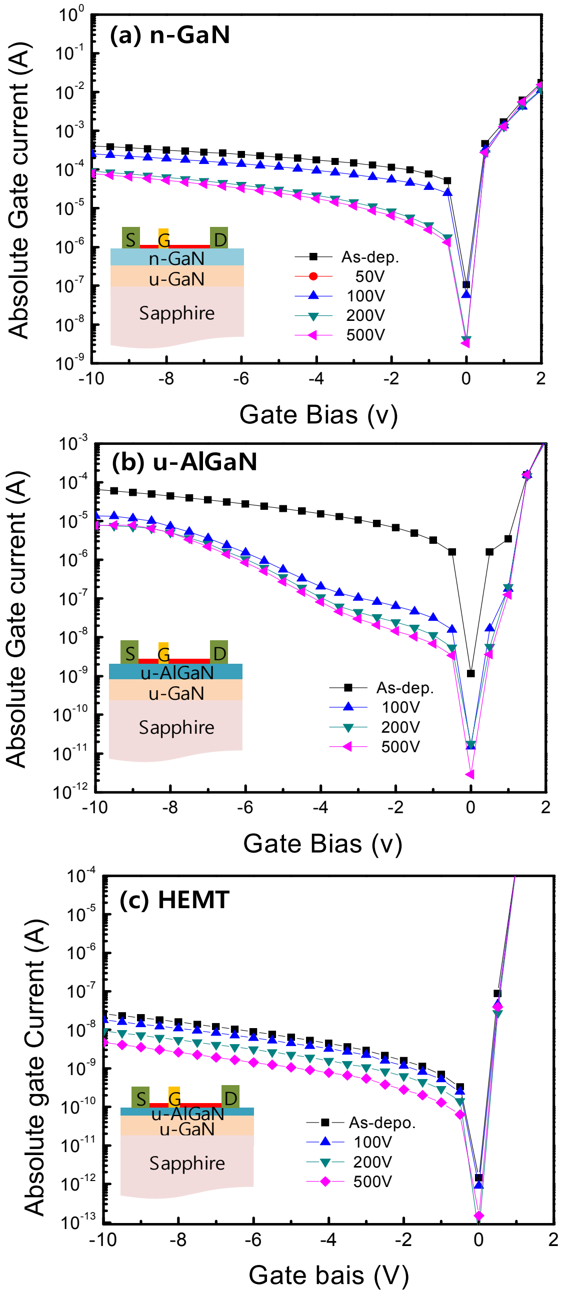

Fig. 3. Gate leakage current of (a) n-GaN:1μm, (b) AlGaN:1μm, (c) HEMT u-AlGaN:25 nm/u-GaN:1μm structure as function of the E-beam irradiation power.

In order to understand the effect of E-beam irradiation on the properties of the surface of epi layer, we have taken XPS measurements before and after E-beam irradiation samples(not shown here). We found that the position of Ga 3d peaks shifted toward lower binding energy after the E-beam irradiation, which implies that the improved leakage characteristics can be attributed to trapping of electrons at the nitrogen vacancies and/or oxygen related defects. The interaction of irradiated electrons with the GaN or AlGaN surface is related to ionization, excitation, bremsstrahlung and pair production. The secondary electrons or rapid electrons caused by the above interactions may result in the recombination of electrons with intrinsic defects and local heating [11].

Fig. 4 shows the maximum drain current of AlGaN/GaN HEMTs with a 5 μm gate length and 200 μm gate width as function of the E-beam irradiation power at 0V, 200V and on the source-to-gate and gate-to-drain spacing region as shown Fig. 1.

The maximum drain current of the HEMTs increased with increasing E-beam irradiation power. This is probably due to the decreased current-collapse-related surface trap density at the AlGaN surface. which is high enough to neutralize the AlGaN polarization charge, thereby eliminating or decreasing the surface related depletion from the dimensional electron gas [12].

Fig. 5 shows the typical transfer characteristics of the devices at a drain bias of 10V. The on-current increased. The threshold voltages of the device shifted toward the reverse direction from -2.65 V to -2.75 V and -2.8 V, respectively. This suggests that E-beam irradiation reduces the trapping effects and decreases the surface traps, such as nitrogen vacancies and oxygen impurities. Therefore, the source-drain current drive capability is improved [13].

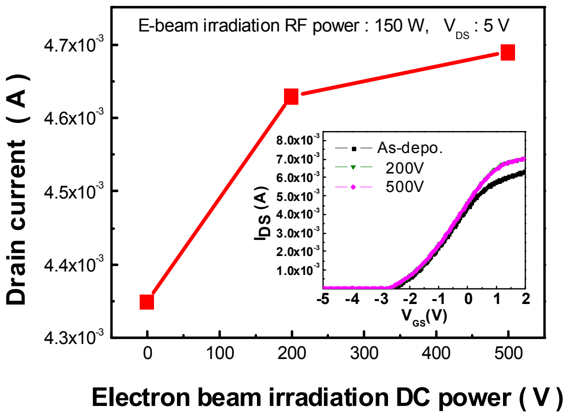

Fig. 4. On current characteristics of AlGaN/GaN HEMT at V_{sd} of 5V, V_{gs} of 0 V as function of the E-beam irradiation voltage. The inset shows transfer characteristics.

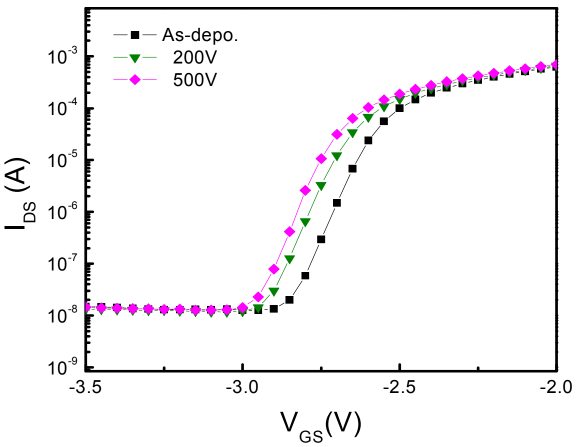

Fig. 5. Transfer characteristics on AlGaN/GaN at V_{SD}:10 V HEMTs as function of E-beam irradiation voltage.

III. CONCLUSIONS

We have investigated improvement of leakage current in GaN, AlGaN and AlGaN/GaN HEMTs employing E-beam irradiation on the source-to-gate and gate-to-drain regions. E-beam irradiation decreased the leakage current by almost one order of magnitude compared to that without E-beam irradiation. Furthermore, the transistor characteristics were improved due to decreased current-collapse-related surface trap density. These results suggest that E-beam irradiation may neutralize the traps and reduce the leakage current.

ACKNOWLEDGMENTS

This study was supported by Basic Science Research Program through the NRF of Korea (No. 2012R1A1A4A01015373), by Center for the Practical Use of Rare Materials, RIC funded by MKE (B0010622).

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