Applied Physics Research; Vol. 4, No. 4; 2012
ISSN 1916-9639 E-ISSN 1916-9647
Published by Canadian Center of Science and Education

AlGaN/GaN High-Electron-Mobility Transistor Using a Trench Structure for High-Voltage Switching Applications

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Received: September 11, 2012 Accepted: September 25, 2012 Online Published: October 10, 2012

doi:10.5539/apr.v4n4p1 URL: http://dx.doi.org/10.5539/apr.v4n4p1

Abstract

We proposed a new AlGaN/GaN high-electron-mobility transistor using a trench structure for high-voltage switching applications. The proposed trench structure was designed for the use at the gate edge, which improved the gate leakage current and breakdown voltage. We considered that the thickness of the AlGaN barrier was related to the polarization, surface-state density and leakage current. The surface states at the gate edge were controlled by etching the AlGaN barrier by 22 nm. The gate leakage current of the proposed device was 40 μA/mm while that of a conventional device was 201 μA/mm with a reverse gate-drain voltage of 100 V. The suppressed gate leakage current may have been caused by the decrease in the surface states at the gate edge. The breakdown voltage of the proposed device was 762 V while that of the conventional device without a trench structure was 120 V. The forward drain current and transconductance of the proposed device were decreased slightly because the channel resistance was increased in the trench region. The results of this study suggest that the trench structure improves the off-state characteristics of GaN power switches.

Keywords: GaN, AlGaN, HEMT, power device, trench, leakage current

1. Introduction

GaN has been found to be a promising material for microwave and high-power applications due to its wide band gap, high critical field, and fast switching speed (Wu et al., 1996; Pearton et al., 1999). A two-dimensional electron gas (Note 1) naturally forms between GaN and AlGaN by polarization. High mobility and high concentration at 2DEG have enabled a low on-resistance, a low power loss, and a high on-current of AlGaN/GaN high-electron-mobility transistors (Note 2) compared with Si MOSFETs (Ibbetson et al., 2000). However, the polarization also induces surface states with shallow energy levels resulting from the charge neutrality. If negative voltage is applied to the gate-drain of AlGaN/GaN HEMTs, the electrons can be trapped in the surface states from the gate (Vetury et al., 2001). The trapping and hopping in the surface states induce leakage current, which decreases the breakdown voltage (Kim et al., 2005). Thus, it is necessary to suppress the surface leakage current for high-voltage switching operations.

We have reported various processes, such as Ni/Au oxidation (Lee et al., 2006), SiO_2 passivation (Ha et al., 2007), As^+ ion implantation into SiO_2 passivation (Lim et al., 2008), and oxygen annealing (Choi et al., 2010) to suppress the leakage current of GaN power devices. We can relax the trapping in the surface states according to the structural design of the device. A field plate was shown to improve the blocking characteristics of AlGaN/GaN HEMTs, which reduces the electric-field peak or electron trapping at the gate (Karmalkar et al., 2001).

The purpose of our work was to report a new AlGaN/GaN HEMT with a trench structure to improve the breakdown voltage. The trench structure was located at the gate edge, which decreased the polarization as well as the surface states locally. This could suppress the leakage current, as assisted by electron hopping. A trench structure under the gate was also demonstrated for the recessed-gate structure of AlGaN/GaN HEMTs (Saito et al., 2006). The recessed-gate structure controlled the threshold voltage from negative to positive. The proposed trench structure was differentiated from the recessed-gate structure because the trench was located at the gate edge and not under the gate. This work was designed to increase the breakdown voltage without a normally-off approach. We fabricated the proposed and conventional devices. The proposed trench structure suppressed the leakage current from 201 to 40 μA/mm at a reverse gate-drain voltage of 100 V. This also improved the breakdown voltage from 120 to 762 V at 1 mA/mm.

2. Fabrication Method

AlGaN/GaN heterostructure was grown on semi-insulating 4H-SiC substrate by metal-organic chemical vapor deposition. Cross-sectional views of the proposed and conventional AlGaN/GaN HEMTs are shown in Figure 1. A nucleation layer, a 3-μm-thick unintentionally doped (Note 3) GaN buffer, a 30-nm-thick UID $Al_{0.26}Ga_{0.74}N$ barrier, and 3-nm-thick UID GaN cap layers were grown in sequence. First, mesa structures were formed to isolate the devices. The 270-nm-deep mesa structure was constructed by Cl_2-based inductively coupled plasma-reactive ion etching (Note 4). A lift-off process was used to define metal patterns. A photolithography of ohmic contacts was processed and native oxides on the contact area were then removed by dipping into a 30:1 buffered oxide etchant. The ohmic contacts of Ti/Al/Ni/Au were evaporated, patterned, and subsequently annealed at 870°C for source and drain electrodes. The respective thicknesses of the Ti/Al/Ni/Au were 20/80/20/100 nm. The ambient condition and the time for the ohmic alloy were N_2 and 30s, respectively. Schottky contacts of Ni/Au/Ni were evaporated and patterned for the gate electrode. The respective Ni/Au/Ni thicknesses were 30/150/30 nm. The proposed trench structure was formed to suppress the leakage current using BCl_3 and Cl_2-based ICP-RIE. The measured depth of the trench structure was 22 nm according to a scanning electron microscope image (Kim et al., 2010). The length of the trench structure was defined as L_t, which was either 2 or 6 μm. Finally, oxygen annealing was performed to resolve any plasma damages on the trench surface. This process was also applied for the conventional devices as a post-annealing step. The temperature and time for the oxygen annealing process were 300°C and 300s, respectively. The gate length, gate-source distance, and gate-drain distance were 3, 3, and 20 μm, respectively.

3. Experimental Results

It was noted that the surface states depend on the polarization between the AlGaN and GaN. When the thickness of the AlGaN barrier was decreased, the surface-states density was reduced due to the weakened polarization. The thicknesses of the trench and the unetched region in the AlGaN barrier were respectively 8 and 30 nm during the fabrication process. Figure 2 shows the schematic band diagram and the charge distribution of the proposed AlGaN/GaN HEMT. The charges of the unetched (Ibbetson et al., 2000) and the trench region in the proposed device can be expressed by the following equations:

$$\sigma^{+}_{polar} = -\sigma^{-}_{polar} \tag{1}$$

$$\sigma^{+}_{surface} + \sigma^{+}_{doping} = -q \times n^{-}_{s} \tag{2}$$

$$\sigma^{+}_{trench} + \sigma^{+}_{doping\_trench} = -q \times n^{-}_{s\_trench} \tag{3}$$

Equation (1) determines the dipoles in the AlGaN barrier. In this equation, σ^{+}_{polar} and σ^{-}_{polar} denote the polarization-induced charges at the AlGaN/GaN interface and on the surface, respectively. These have different polarities with the same absolute value because they are dipoles. Equations (2) and (3) represent the charge neutrality at the unetched and trench region, respectively. In this equation, $\sigma^{+}_{surface}$, σ^{+}_{doping}, and $-q\times n^{-}_{s}$ are the surface states, ionized donors in the AlGaN barrier, and the 2DEG density in the unetched region, respectively. In addition, σ^{+}_{trench}, $\sigma^{+}_{doping\_trench}$, and $-q\times n^{-}_{trench}$ are also the surface states, the ionized donors in the AlGaN barrier, the 2DEG density in the trench region, respectively. Moreover, σ^{+}_{doping} or $\sigma^{+}_{doping\_trench}$ are not significant because the AlGaN barrier is not doped. The $|-q\times n^{-}_{s\_trench}|$ value is less than that of $|-q\times n^{-}_{s}|$ because the polarization is decreased in the trench region, implying that the forward I-V of the proposed device is degraded more than that of the conventional device. However, σ^{+}_{trench} is less than $\sigma^{+}_{surface}$; therefore, the trench structure can suppress the leakage current by means of electron hopping in the surface states.

The proposed AlGaN/GaN HEMTs using the trench structure were fabricated and the electric characteristics were then measured. The measured breakdown voltages of the proposed and conventional devices are shown in Figure 3. The destructive breakdown voltage meant that the maximum reverse voltage induced thermal runaway and burn-out at the contacts. The destructive breakdown voltages of the proposed devices were 1160 and 1068 V at L_t values of 2 and 6 μm, respectively. The destructive breakdown voltage of the conventional device was 962

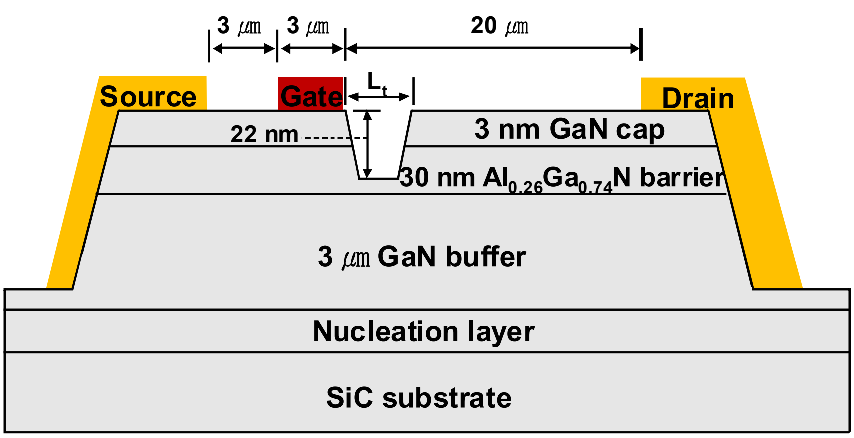
V. If the breakdown voltage was defined at a leakage current of 1 mA/mm, the breakdown voltages of the proposed devices were 762 and 688 V at L_t values of 2 and 6 µm, respectively. The conventional device showed a breakdown voltage of 120V. The trench structure decreases the surface states and electron trapping at the gate edge, which improves the breakdown voltage. The long L_t accounts for the high-plasma damage, which degrades the breakdown voltage slightly. The measured gate leakage currents of devices are shown Figure 4. The gate leakage current was measured at a reverse gate-drain voltage ranging of 0 to 100 V. The gate leakage currents of the proposed devices with L_t values of 2 and 6 µm were 40 and 60 µA/mm, respectively. The conventional device exhibited a gate leakage current of 201 µA/mm. The trench structure improves the leakage current as well as the breakdown voltage. The proposed device with a short L_t also achieves a low leakage current.

The output I-Vs of the devices were measured at gate-source voltage of -5, -3, -1, and 1 V. The measured output I-Vs of devices are shown in Figure 5. When the gate-source and drain-source voltages were 1 and 10 V, the saturation currents of the proposed devices were 461 and 427 mA/mm at L_t values of 2 and 6 µm, respectively. The conventional device had a saturation current of 503 mA/mm. The proposed device achieves a higher on-resistance and a lower saturation current than the conventional device. The trench structure decreases the 2DEG density locally, which increases the channel resistance. The knee voltage is the drain-source voltage where the forward drain current begins to become saturated. This is increased with a long L_t because the channel resistance is increased.

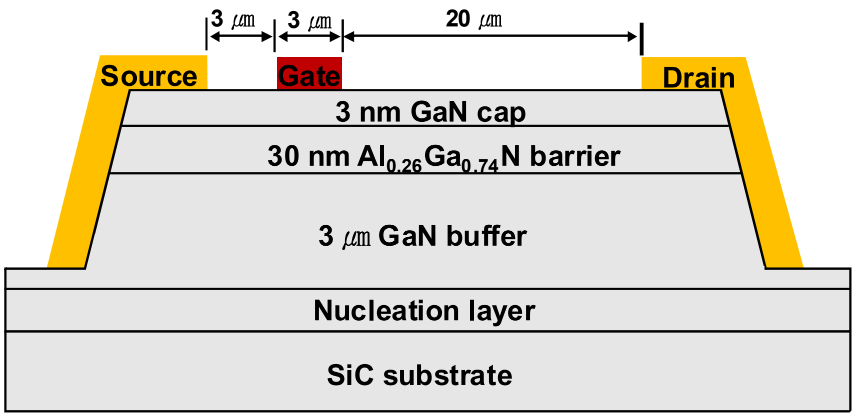
The transfer I-Vs of the devices were also measured at a drain-source voltage of 5 V. The measured transfer I-Vs of the devices are shown in Figure 6. The trench structure slightly decreased the maximum transconductance. The maximum transconductance values of the proposed devices were 102 and 98 mS/mm at L_t values of 2 and 6 µm, while that of the conventional device was 105 mS/mm. The decrease of transconductance in the proposed devices was caused by the decreased 2DEG density at the gate edge. The threshold voltage of the proposed device was shifted by approximately 0.2 V toward the positive direction compared to that of the conventional device. The low-density channel under the gate edge depletes easily upon the reverse voltage. The proposed trench structure for AlGaN/GaN HEMTs is suitable for power devices because the leakage current and breakdown voltage are improved.

4. Conclusions

The proposed trench structure was fabricated at the gate edge of a high-voltage AlGaN/GaN HEMT. The depth of the trench structure was 22 nm, where the thickness of the AlGaN barrier was 30 nm. The trench structure at the gate edge decreased the surface states locally and suppressed the surface leakage current. The gate leakage current was suppressed from 201 to 40 µA/mm due to the trench structure. The low leakage current due to the proposed trench structure led to a high breakdown voltage. The proposed device achieved a high breakdown voltage of 762 V, whereas the conventional device exhibits a low breakdown voltage of 120 V. The results of this study suggest that the trench structure at the gate edge is suitable as a high-voltage technique in GaN power devices.



(a)



(b)

Figure 1. Cross-sectional views of (a) the proposed and (b) the conventional AlGaN/GaN HEMT

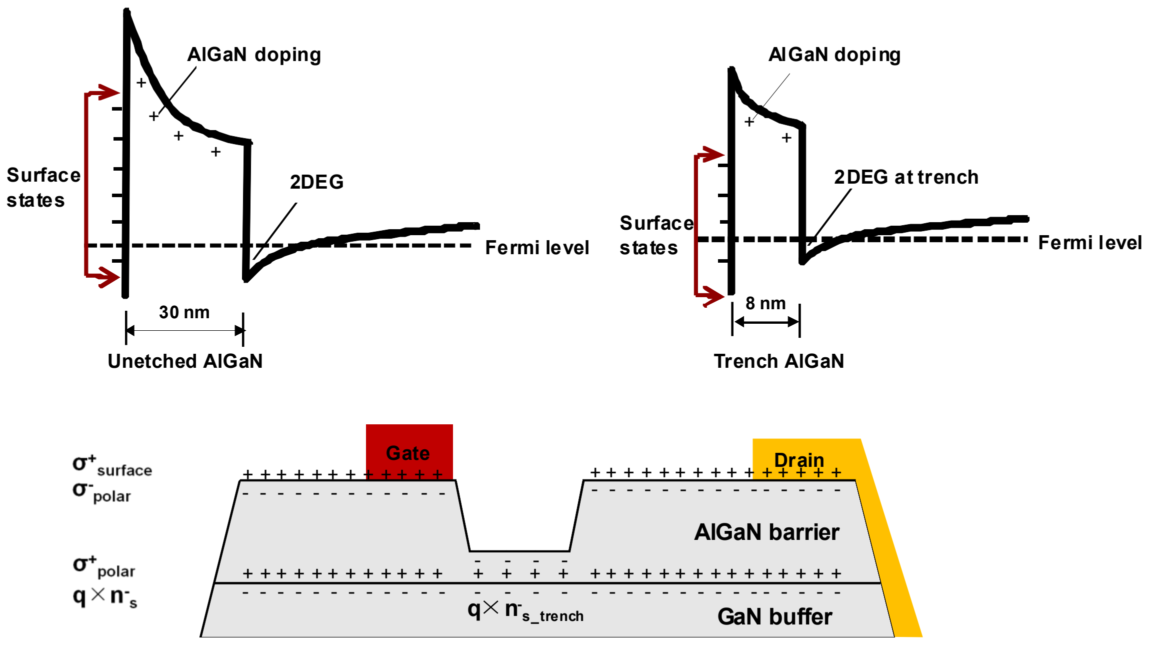


Figure 2. Band-diagram and charge distribution of the proposed AlGaN/GaN HEMT

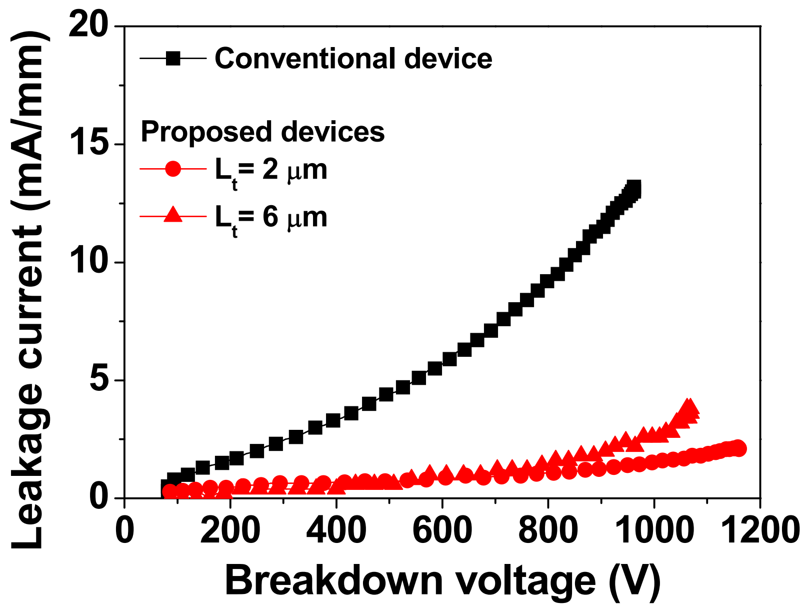


Figure 3. Measured breakdown voltages of the proposed and the conventional AlGaN/GaN HEMTs

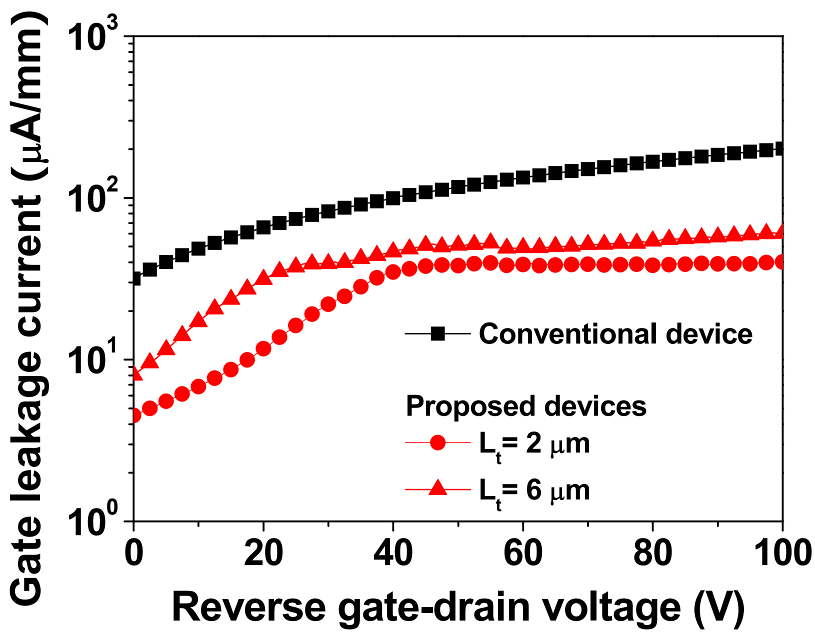


Figure 4. Measured gate leakage currents of the proposed and the conventional AlGaN/GaN HEMTs

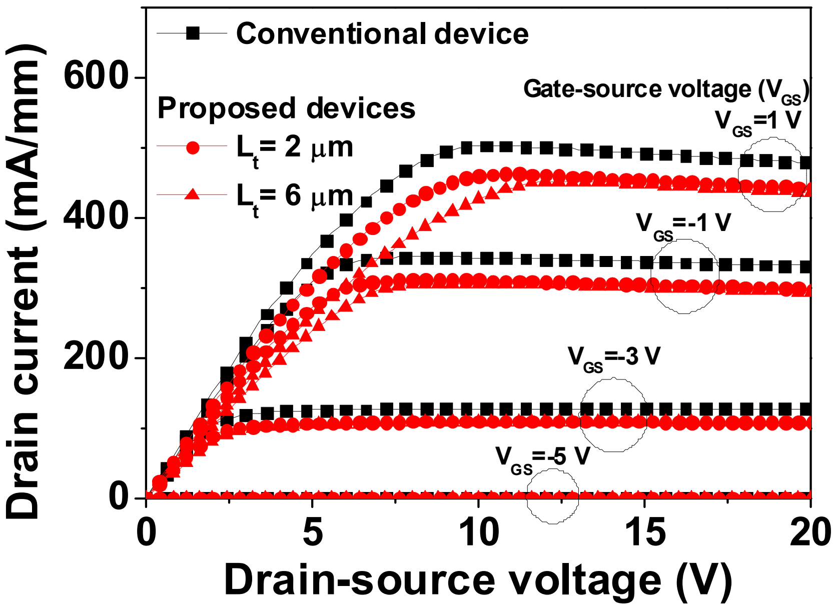


Figure 5. Measured output I-Vs of the proposed and the conventional AlGaN/GaN HEMTs

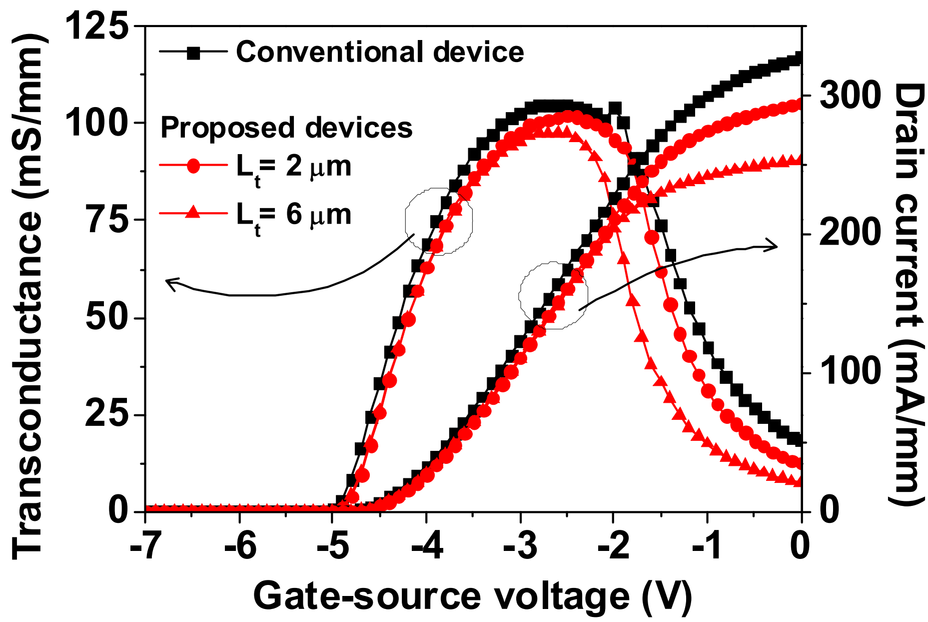


Figure 6. Measured transfer I-Vs of the proposed and the conventional AlGaN/GaN HEMTs

Acknowledgements

This work was supported by Seoul National University Information Technology Group of the BK21 research program funded by the Korean Government's Ministry of Education, Science, and Technology.

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Notes

Note 1. This abbreviation was 2DEG.

Note 2. This abbreviation was HEMT.

Note 3. This abbreviation was UID.

Note 4. This abbreviation was ICP-RIE.