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High performance of AlGaN/GaN HEMTs using buffer-free GaN on SiC structure

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Abstract

This paper reports on the processing and device characteristics of AlGaN/GaN high electron mobility transistors using buffer-free GaN grown on SiC substrate. This new concept of thin AlGaN/GaN heterostructure (<330nm of epitaxial layers) as compared to a conventional structure with a thick GaN buffer layer (>2-3µm). As-grown epitaxial structure provides a two-dimensional electron gas (2DEG), n_s, of 1 x 10^{13} cm^{-2}, an electron mobility, µ, of > 2000 cm^2/V.s, and sheet resistance, R_{sh}, of 330 Ω/□. The fabricated AlGaN/GaN HEMT buffer-free GaN with a 3-µm gate long, two-finger 2 × 50 µm wide device demonstrates a maximum drain current density of 801 mA/mm at V_{GS} = 2 V and maximum peak transconductance of 189 mS/mm at V_{DS} = 5 V. This device also produces low gate leakage currents of I_{GS} = 2.1x10^{-4} A/mm at V_{GS} = -10 V and a breakdown voltage, V_{BR}, of over 200 V. The maximum cut-off frequency, f_T, and maximum oscillation frequency, f_{max}, of 4.7 GHz and 9.4 GHz were obtained respectively. These results indicate the potential of using buffer-free GaN heterostructure for future high power high frequency applications.

Introduction

AlGaN/GaN high electron mobility transistors (HEMTs) are mostly widely used in applications that require high-power at high-frequencies, because of their high electric field, high mobility, and the excellent physical properties of III-V nitride heterostructure material [1]. In conventional AlGaN/GaN heterostructures grown on silicon carbide (SiC), sapphire (Al_2O_3), or silicon (Si), the buffer needs to be thick enough to minimize the growth defects due to the lattice mismatch between the GaN and the substrate [2]. It was reported that these defects can affect the electron mobility in the two-dimensional electron gas (2DEG) thus reducing device performance [2]. This buffer layer also needs to be highly resistive, achieved by the introduction of iron (Fe) or carbon (C) type dopants, to reduce the leakage current, improve the breakdown voltage, enhance the carrier confinement in the 2DEG and exclude the parasitics near to GaN channel [3]. However, this intentional doping introduces large trapping effects in the buffer layer close to the GaN channel [4] which can cause current collapse, gate lag and drain lag and so affecting the overall performance of AlGaN/ GaN HEMT devices [5]. Recently, a few works have been reported using the buffer-free GaN heterostructure in which the HEMT devices were successfully fabricated on a thin unintentionally doped (UID) GaN layer grown on the high quality thin AlN nucleation layer [6]. The demonstrated devices were comparable with the devices fabricated on the conventional heterostructure employing a thick GaN buffer layer [7]. In this work, we discuss the fabrication and device characteristics of a buffer-free GaN heterostructure. Details of processing steps, DC and RF characteristics of the devices are included in the next sections of the paper.

Device Structure and fabrication

The epitaxial structure used in this work was grown by SweGaN, using hot wall metal oxide chemical vapour deposition (MOCVD) on a semi-insulating SiC substrate. The wafer structure consists of (from top to bottom), a 2 nm GaN cap layer, 14 nm AlGaN barrier layer with 30 % Al mole concentration, thin 250 nm unintentionally doped (UID) GaN channel layer grown on high quality 60 nm AlN nucleation layer. The high-quality thin GaN is enabled by the transmorphic epitaxial growth of AlN nucleation layer on SiC substrate [8]. As-grown epitaxial layer provides a two-dimensional electron gas (2DEG), n_s, of 1 x10^{13} cm^{-2}, an electron mobility, µ, of > 2000 cm^2/V.s, and sheet resistance, R_{sh}, of 330 Ω/□. These values show that the 2DEG transport properties were not compromised when significantly reducing the GaN channel layer thickness.

Device fabrication started with the Ohmic metal contacts formed by evaporation of Ti/Al/Ni/Au, followed by a lift-off process, then annealed at 800 °C for 30 secs. Next, mesa isolation was performed using Cl_2/Ar gases providing etch depth of 100 nm. Gate metal contacts were formed by evaporation of Ni/Au. This is followed by a blanket deposition of 100 nm of Si_3N_4 grown using plasma-enhanced chemical vapour deposition (PECVD) at 300 °C for surface passivation. Then, Si_3N_4, layer in the Ohmic regions was etched using SF_6/N_2 gases prior to bond pad metal contacts deposition. All fabrication steps were defined using photolithography. DC and RF measurements were made at room temperature using Keysight's B1500A Semiconductor Device Analyzer and E8361A PNA Network Analyzer, respectively. The cross-section schematic diagram of the fabricated AlGaN/GaN HEMTs using buffer-free GaN on SiC substrate is shown in Figure 1. Device dimensions used in this work are as follows: gate length, L_G = 3 µm, gate-to-source distance, L_{GS} = 2 µm, gate-to-drain distance, L_{GD} = 3 µm, and gate width = 2 x 50 µm.

Results and discussion

Figure 2 shows the output device characteristics, while Figure 3 shows both the transfer characteristics and the transconductance, respectively. The maximum current density, $I_{DS(max)}$, and maximum peak transconductance, $g_{m(max)}$, were 801 mA/mm at V_{GS} = 2 V and 189 mS/mm at V_{DS} = 5 V. The obtained results show an expected higher $I_{DS(max)}$ and $g_{m(max)}$ compared to the previous published work using the similar AlGaN/GaN buffer-free GaN structure with device gate length of 5 µm [9]. The contact resistances were measured using the linear transmission line model (TLM) structures and provide an average value of 0.62 Ω.mm. Figure 4 shows a plot of the measured gate leakage current characteristics of I_{GS} = 2.1x10^{-4} A/mm at V_{GS} = -10 V, while the measured breakdown voltage, V_{BR}, exceeds the maximum compliance of measurement set up of 200 V as shown in Figure 5. The small signal RF performance of the device is shown in Figure 6. The measured maximum cut-off frequency, f_T, and maximum oscillation frequency, f_{max}, of 4.7 GHz and 9.4 GHz were obtained for a two-finger 2 x 200 µm device biased at V_{DS} = 15 V and V_{GS} = -1.2 V. The parasitic effects of the band pads were not de-embedded.

Conclusions

We have successfully fabricated and measured AlGaN/GaN HEMT buffer-free GaN grown on SiC substrate. Good DC device characteristics have been demonstrated. These results indicate the potential of AlGaN/GaN HEMT buffer-free GaN for future high frequency power applications. This work will be implemented in the fabricating of submicron length devices (L_G ≤100 nm) utilizing the T-gate technology to further optimize the device performance for use in the W-band (75-110 GHz) frequency applications.

Acknowledgments

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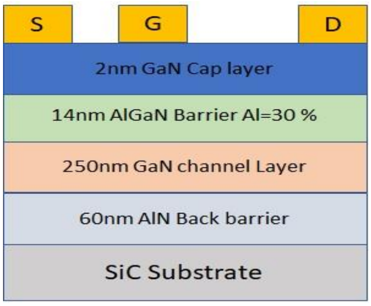

Figure 1. Schematic diagram of fabricated buffer-free AlGaN/GaN HEMT structure. The total thickness of the epitaxial layers is only 326nm.

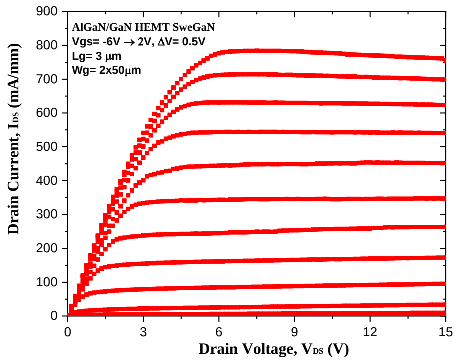

Figure 2. Measured drain current with gate to source voltage swept from -6V to 2 V (Step size of 0.5V)

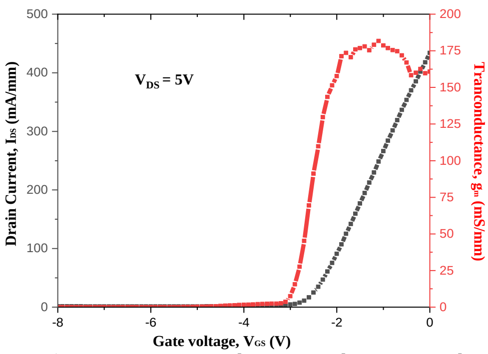

Figure 3. Measured transconductance and transfer characteristics at drain to source voltage V_{DS}= 5V.

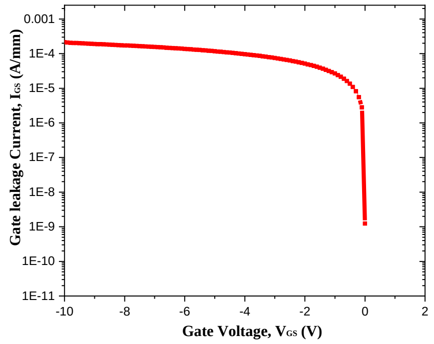

Figure 4. Measured leakage of the 3-µm long, 2x50µm wide device at V_{DS}= 0V.

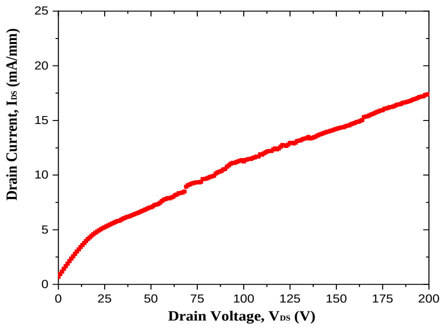

Figure 5. Measured off-state breakdown voltage with V_{GS}= -6V.

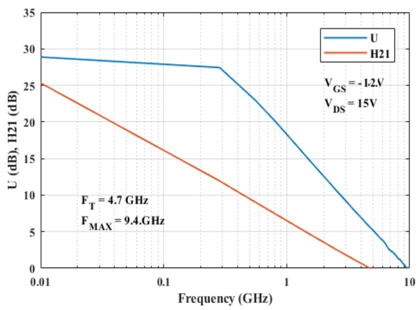

Figure 6. Cut-off frequencies of the 3-µm gate long, 2x200µm wide device.