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2.3 nm barrier AlN/GaN HEMTs with insulated gates

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Ultra-shallow channel AlN/GaN high electron mobility transistor (HEMT) structures with a 2.3 nm AlN barrier were grown by plasma-assisted molecular beam epitaxy (PAMBE) on sapphire substrates. They exhibit 2-D electron gas densities of ~ 1.4 x 10^{13} cm^{-2} and electron hall mobilities of ~ 1600 cm^2/Vs. Insulated-gate stacks of SiN_x/Al_2O_3/Ni/Au were used to suppress the gate leakage current, which is found to largely stem from dislocation-assisted leakage paths. AlN/GaN HEMTs with 250 nm gate length showed DC output current densities of up to 1.6 A/mm, transconductances of ~ 300 mS/mm, and extrinsic f_t/f_{max} of 24/52 GHz. These performance metrics demonstrate that these ultra-shallow channel AlN/GaN heterostructures hold a lot of promises for high-power high-frequency device applications.

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1 Introduction Downscaling of AlGaN/GaN HEMTs has attracted intense interest in order to achieve higher speed operation [1]. Reduction of gate length down to tens of nanometers demands sub-10nm thick gate barriers in order to avoid severe short-channel effects [2]. Jessen et al. [3] recently proposed a minimum aspect ratio (L_G/t_{bar}) of 15 for AlGaN/GaN HEMTs to mitigate the short-channel effects based on wide samplings of multiple material sources and barrier thicknesses, where L_G is the measured metallurgical gate length and t_{bar} the AlGaN barrier thickness. This ratio is significantly higher than the conventional GaAs wisdom ($L_G/t_{bar} > 2.5 – 6$). Since the all-binary AlN/GaN heterostructure can offer two-dimensional electron gas (2DEG) densities in excess of $1x10^{13}$ cm^{-2} with electron mobility higher than 1000 cm^2/Vs for AlN barrier as thin as ~ 2.0 nm [4], together with the large bandgap of AlN (6.2 eV), ultra-thin barrier AlN/GaN heterostructures seem to be ideal candidates for high-speed high-power applications. AlN was explored as a gate insulator for GaN:Si channel field effect transistors (FETs) in early stages [5]. Not until recently were the undoped AlN/GaN heterostructures employed for heterojunction FETs (HFETs). With the aid of a thin SiN_x layer (3 nm) deposited by catalytic chemical vapor deposition (CAT-CVD), a 2DEG density of ~ 2.33 x 10^{13} cm^{-2} with an electron mobility of 365 cm^2/Vs was obtained in a AlN/GaN heterostructure with 2.5 nm AlN barrier [6]. The resultant HFETs showed an output current of ~ 1 A/mm, an intrinsic current-gain cut-off frequency f_t of 107 GHz and power-gain cut-off frequency f_{max} of 160 GHz. These devices had relatively low electron mobilities, yet exhibit excellent high frequency performance. With improvement of the transport properties, major improvement in the device performance can be expected. In this letter, we present the first step towards that direction.

2 Experiments The device structure consists of a 200 nm unintentionally doped GaN layer capped with a 2.3 nm AlN barrier, grown by a Veeco Gen 930 PAMBE system, on commercially available MOCVD-grown semi-insulating GaN on sapphire templates. The typical 2DEG carrier density at the as-grown AlN/GaN interface obtained by Hall measurements is ~ 1.4 x 10^{13} cm^{-2} with room temperature electron mobility of ~ 1600 cm^2/Vs, resulting in a sheet resistances of ~ 350 ohm/sq. In the investigation of ohmic contacts, samples with lower carrier mobilities were also used, but with the same AlN thickness thus similar carrier densities.

In order to protect the device surface as well as investigate the effect of a thin layer of SiN_x on ohmic contact formation, a 3 nm thick SiN_x was first deposited over the entire sample surface by plasma-enhanced CVD (PECVD).

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The device mesa was formed using BCl_3/Cl_2 reactive ion etching (RIE). Ti/Al/Ni/Au ohmic metal stack was deposited by e-beam evaporation. Rapid thermal annealing at 860 °C yielded contact resistances typically of ~ 1.5 ohm-mm with very smooth morphology. Finally submicron gates of 250 nm were defined by e-beam-lithography, followed by e-beam deposition of 3 nm Al_2O_3 and Ni/Au. The source-drain distance is 1.5 µm. A schematic and a SEM picture of the device structure are shown in Fig. 1.

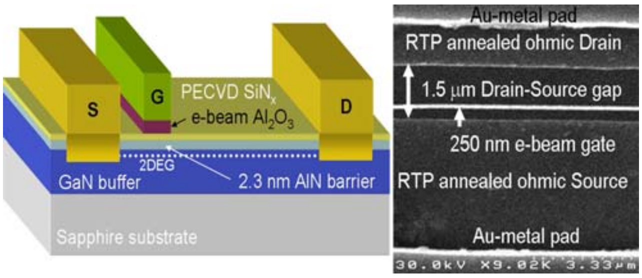

Figure 1 Schematic cross-section and SEM top view of AlN/GaN HEMTs with insulated gates.

3 Results and discussion

Since the AlN barrier is very thin, tunneling current could be a serious concern. In order to understand such limitations in the current device structures, Ni/Au-Schottky gate diodes were also fabricated and tested.

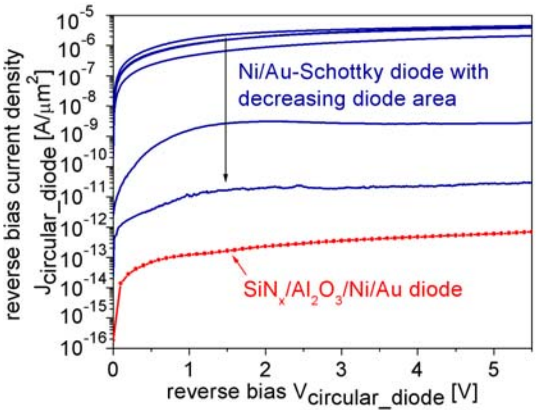

Figure 2 Reverse bias current density of circular gate diodes with gate metal stack of Ni/Au and composite gate stack of SiN_x/Al_2O_3/Ni/Au (diode diameter of 40, 20, 15, 10 and 5 µm).

Shown in Fig. 2, the reverse bias current density was found to dramatically decrease with decreasing diode area. This indicates the observed high leakage current can be largely attributed to the dislocations in the samples, whose density is quite high ~ 1 x 10^9 cm^{-2}. In order to suppress gate leakage, a composite gate stack of SiN_x/Al_2O_3/Ni/Au is therefore adopted in this study. For the gate diodes with this insulated composite stack, the reverse bias current was observed to reduce as well as scale proportionally with the diode area, also shown in Fig. 2.

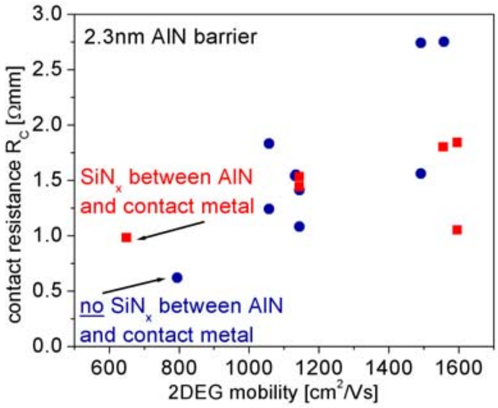

Figure 3 Contact resistances of annealed ohmics on AlN/GaN heterostructures with 2.3 nm AlN barrier as a function of 2DEG mobility.

Shown in Fig. 3 are the contact resistances of alloyed ohmics obtained on 2.3 nm AlN/GaN heterostructures with similar 2DEG densities, but different electron mobilities. Interestingly, it was found that without a thin layer of SiN_x the ohmic contact resistance strongly depends on the heterostructure quality (2DEG mobility): the higher the electron mobility, the higher the contact resistance. The same phenomenon was also observed in heterostructures with other AlN thicknesses and the possible mechanisms for this effect are described in Ref. [7] and [8].

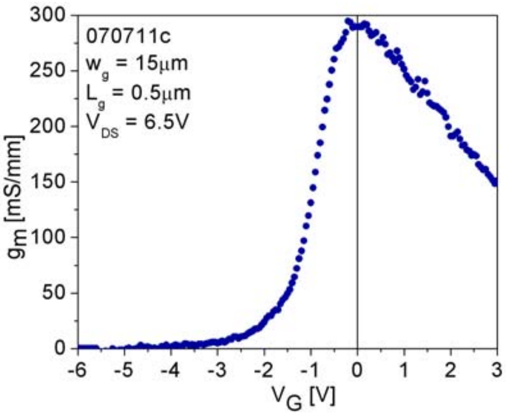

Figure 4 The highest measured transconductance on AlN/GaN HEMTs with insulated gates, ~ 300 mS/mm.

By inserting a thin layer of PECVD SiN_x between the ohmic metal stack and the heterostructure, the similar contact resistances and dependence on carrier mobilities were observed. The little difference in ohmic contact formation between samples with and without SiN_x can be attributed to the existence of 2DEGs in these as-grown heterostructures. On the other hand, it was necessary for Higashiwaki et al. to employ a thin layer of CAT-CVD SiN_x to induce 2DEG that otherwise did not exist in his heterostructures.

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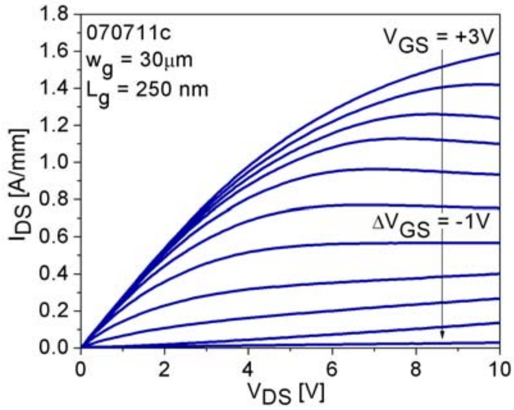

Figure 5 DC family I-Vs of AlN/GaN insulated gate HEMTs showing a maximum current density of 1.6 A/mm.

The transconductance g_m and DC output characteristics of the resultant HEMTs with insulated gates are shown in Fig. 4 and Fig. 5, respectively. The highest measured g_m of 300 mS/mm was seen in a device structure with a 15 µm wide and 500 nm long gate. A remarkably high current of 1.6 A/mm was observed in devices with gate width of 30 µm and gate length of 250 nm despite the high contact resistance. The relatively high pinch-off voltage was found to be due to the conducting re-growth interface situated ~ 200 nm below the sample surface. An extrinsic current-gain cut-off frequency f_t of 24 GHz and a power-gain cut-off frequency f_{max} of 52 GHz was measured (Fig. 6) on the same device. Not shown here, the breakdown voltage was found to be > 20 V.

Carrier confinement and gate modulation in these devices are still largely limited by the heterostructure quality as well as the gate dielectric. With further optimization in material quality and ohmic contacts, higher current and transconductance can be expected. However, in spite of the high ohmic contact resistances and un-optimized gate dielectric, the demonstrated DC and small signal device performances are very encouraging, indicating that HEMTs based on ultra-shallow channel AlN/GaN structures hold a lot of promises for high-speed high-power applications owing to their ultra-scaled geometry.

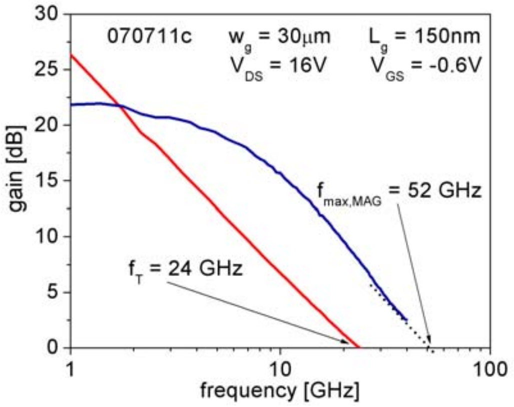

Figure 6 Small signal performance of the device shown in Fig. 5, measured at V_{DS} = 16 V and V_{GS} = - 0.6 V.

4 Conclusion

HEMTs based on AlN/GaN heterostructures with the AlN barrier as thin as 2.3 nm are investigated. Employing a composite insulated gate stack of SiN_x/Al_2O_3/Ni/Au, a very high DC output current density of ~ 1.6 A/mm and a transconductance of ~ 300 mS/mm were demonstrated. The insulated gate stack effectively suppresses the gate leakage. A f_t of 24 GHz and f_{max} of 52 GHz were measured. With optimization of material quality as well as ohmic contacts and gate dielectrics, vast improvements in device performance can be expected.

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