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Quasi-enhancement mode AlGaN/GaN HEMTs on sapphire substrate

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Abstract

In this study, quasi-enhancement mode AlGaN/GaN HEMT devices with the gate length of 1-μm are fabricated using a conventional method (i.e. without gate-recessing process) and the direct current and radio frequency characteristics of these devices are investigated. The threshold voltages are in the range of −0.3 to −0.5 V. The devices exhibit a maximum drain current of 280 mA/mm at a gate bias of 2 V. The pinch off voltage is about −1.0 V. At the gate bias of 1.5 V and the drain bias of 6 V, the devices exhibit an extrinsic transconductance of 140 mS/mm, a unity current gain cutoff frequency (f_T) of 4.3 GHz, and a maximum oscillation frequency (f_{MAX}) of 13.3 GHz, respectively.

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1. Introduction

There have been extensive efforts to develop GaN and the related alloys for electronic device applications. GaN-based HEMT studies have been concentrated on the development of microwave power devices. Up to now, efforts have been focused on the depletion mode AlGaN HEMTs devices with pinch-off voltages typically in the range of −4 to −8 V, which have demonstrated excellent microwave power performances [1,2]. Enhancement-mode GaN-based HEMTs are of interests because they can be integrated with the depletion-mode devices to form complementary circuits. However, high polarization charge density at the interface between AlGaN and GaN limits the fabrication of enhancement mode HEMT devices. An enhancement mode AlGaN/GaN HEMT requires theoretically about several nanometer AlGaN thickness and about 20% of Al mole concentration. Khan et al. [6] reported an enhancement mode AlGaN/GaN HFET using a low pressure MOCVD system. In this enhancement device, a much thinner AlGaN layer with the thickness of 10 nm compared to that of depletion mode devices was used. With the use of a thin barrier layer and the adjustment of the barrier layer doping, the threshold voltage of 0.05 V was achieved. However, the dc transconductance was only 23 mS/mm for a device with 1 μm gate length and 5 μm drain to source separation. To improve device performance, a few attempts to fabricate the enhancement mode devices have been performed. Using a gate-recessing process, the threshold voltage can be controlled by the etching depth [1,4,5]. Moon et al. [3] reported the fabrication of the enhancement mode AlGaN/GaN HEMTs with 0.2 μm gate length and 200 μm gate width using a gate recessing process. These devices exhibited a maximum drain current density of 100 mA/mm, a peak transconductance (g_m) of 85 mS/mm, an unity current gain cut-off frequency (f_T) of 24 GHz, and a maximum oscillation frequency (f_{MAX}) of 45 GHz.

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These performances are limited due to large access resistance. Hu et al. [7] fabricated an enhancement mode AlGaN/GaN HEMTs with a gate length of 10 μm and a gate width of 150 μm by using selectively grown pn junction gate. This selective growth technique allowed both enhancement and depletion mode to be fabricated on the same wafer, thus, provided the possibility for the low consumption GaN-based logical integrated circuits. However, this enhancement device still showed very small g_m value of 10 mS/mm and the maximum saturation current of 40 mA/mm at a gate bias of 4 V.

In this study, quasi-enhancement mode AlGaN/GaN HEMT devices with 1-μm gate length are fabricated with no gate-recessing and DC and RF characteristics of these devices are investigated.

2. Device layer structure and fabrication

The device cross section is shown in Fig. 1. The epilayer of AlGaN/GaN HEMT structure shown in Fig. 1 was grown by metal-organic chemical vapor deposition (MOCVD) on a (0 0 0 1) sapphire substrate. The epilayer consists of 40 nm AlN nucleation layer, 3 μm of undoped GaN, and 20 nm undoped $Al_{0.25}Ga_{0.75}N$. Hall measurements indicated that the layer had a two-dimensional sheet carrier density of $\sim 9 \times 10^{12}$ cm^{-2} and an electron mobility of 1100 cm^2/v s at room temperature, respectively. Device isolation was performed by mesa dry etching using an inductively coupled plasma reactive ion etching system in a chlorine-based plasma and using photoresist as an etch mask. Ti/Al/Mo/Au drain–source ohmic contacts were deposited using electron beam evaporation and annealed at 900 °C for 30 s in a rapid thermal annealing system. The ohmic contact resistivity was determined typically to be 4×10^{-8} $\Omega\,cm^{-2}$ using transfer length measurement patterns, hence, excellent source access resistance was achieved. Ni/Au metallization was used for Schottky gate contacts with a gate length of 1 μm. The devices have a gate width of 100 μm and the source to drain spacing of 3 μm. All patterning were performed using optical contact lithography.

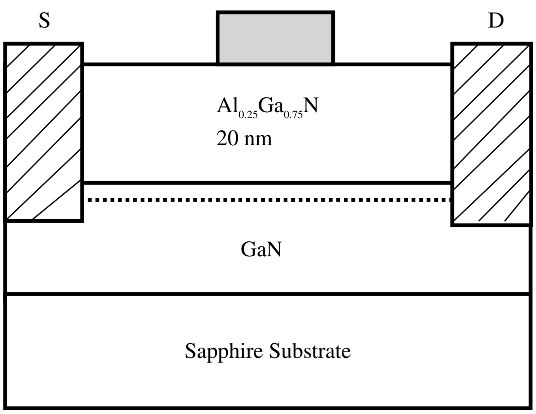

Fig. 1. AlGaN/GaN HEMT layer structure.

3. Results and discussion

The measurements of DC and microwave characteristics were performed using Agilent 4156C semiconductor parameter analyzer and Agilent 8510C network analyzer. Fig. 2 shows the typical drain current–voltage characteristics of the *T*-configuration HEMT devices with 1-μm gate length and 100-μm gate width. The gate bias is in the range of −1.5 to 2 V with the step of 0.5 V. The maximum drain current at a gate bias of 2 V is 280 mA/mm and the drain current at a gate bias of 0 V (V_{dss}) is 59 mA/mm. The knee voltage is about 1.5 V. These devices have the typical pinch-off voltage of about −1.0 V. Generally, depletion mode AlGaN/GaN HEMT devices have very high pinch-off voltages, typically in the range of −4 to −8 V. Some of the devices clearly show kinks in the drain characteristics. This effect is attributed to the hot electron injection and trapping in the buffer layer [5]. The drain current–voltage characteristics at the higher bias voltages exhibit negative differential resistance characteristic due to the self-heating effect and the poor thermal conductivity of the sapphire substrates [8]. The maximum drain current value of our devices is larger than those of reported enhancement mode HEMT devices fabricated with other techniques. As mentioned earlier, the maximum drain current of the enhancement

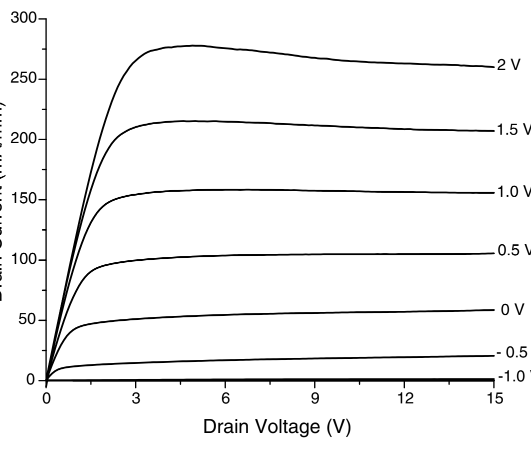

Fig. 2. DC *I–V* characteristics of a 1 μm AlGaN/GaN HEMT with a gate width of 100 μm. The gate was biased from −1.5 to 2 V.

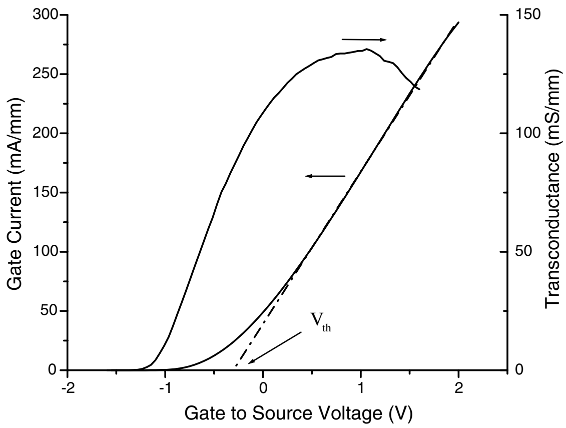

Fig. 3. DC transfer characteristics of an AlGaN/GaN with a gate width of 100 μm and a gate length of 1 μm. The threshold voltage of the device is −0.3 V.

mode devices with gate recessing was 100 mA/mm and that of devices with selectively grown pn junction gate was only 40 mA/mm even at the gate bias of 4 V.

The typical DC transfer characteristics of the devices are shown in Fig. 3. A maximum extrinsic transconductance (g_m) of 140 mS/mm is obtained at a gate voltage of 1.4 V and at a drain bias voltage of 3.5 V. This peak g_m value is much lager than that of devices fabricated by gate-recessing or selectively grown pn junction gate technologies. The peak g_m of the enhancement mode devices with gate recessing was 85 mS/mm and that of devices with selectively grown pn junction gate was only 10 mS/mm, respectively. From the gate-bias intercept of the extrapolation of drain current curve at the peak g_m position in the transfer characteristics, the threshold voltages are determined in the range of −0.3 to −0.5 V depending on drain bias voltages. These threshold voltages are much smaller than those of the typical values of conventional AlGaN/GaN HEMTs, which are typically in the range of −5 to −8 V. The small signal RF measurements of 1-μm enhancement mode AlGaN/GaN HEMTs were performed in the range of 1–50 GHz. Fig. 4 shows the plots of current gain and maximum stable power gain (MSG) and maximum available gain (MAG) versus frequency. The devices with a gate length of 1 μm exhibited an f_T of 4.3 GHz and an f_{MAX} of 13.3 GHz at a gate bias of 1.5 V and a drain bias of 6 V. According to our knowledge, these are the highest reported values for GaN-based enhancement devices with the same gate length. With further optimization of device structures, GaN-based enhancement mode HEMTs with better device performances are expected in the near future.

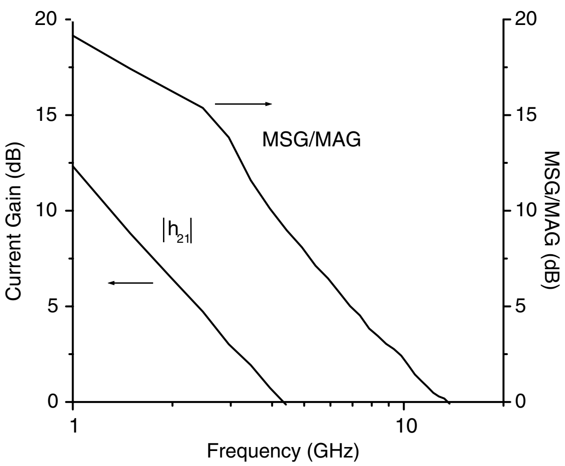

Fig. 4. Current gain and maximum stable power gain versus frequency of an AlGan/GaN with a gate width of 100 μm and a gate length of 1 μm. The gate bias is 1.5 V and a drain bias is 6 V.

4. Conclusions

Quasi-enhancement mode AlGaN/GaN HEMT devices with 1-μm gate length are fabricated without using gate-recessing process or selectively grown pn junction gate technique. These quasi-enhancement mode devices exhibit the threshold voltage of as low as −0.3 V, a g_m of 140 mS/mm, an f_T of 4.3 GHz, and an f_{MAX} of 13.3 GHz, respectively. Further improvement of enhancement-mode GaN-based HEMT devices is desired for applications of complementary integrated circuits.

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