High Performance AlGaN/GaN HEMTs on Semi-Insulating SiC Substrates Grown by Metalorganic Chemical Vapor Deposition

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Abstract

The performance of an innovative delta-doped AlGaN/AlN/GaN high-electron-mobility transistor (HEMT) structure is reported. The epitaxial heterostructures were grown on semi-insulating SiC substrates by low-pressure metalorganic chemical vapor deposition. These structures exhibit a maximum carrier mobility of 1,058 cm^2/V-s and a sheet carrier density of 2.35×10^{13} cm^{-2} at room temperature, corresponding to a large $n_s\mu_n$ product of 2.49x10^{16} /V-s. HEMT devices with 0.25 µm gate length were fabricated and exhibited a maximum current density as high as 1.5 A/mm (at V_G = +1V) and a peak transconductance of g_m = 240 mS/mm. High-frequency device measurements yielded a cutoff frequency of f_t ~ 50 GHz and maximum oscillation frequency f_{max} ~ 130 GHz.

INTRODUCTION

Microwave power devices based on GaAs have almost reached their power limits, whereas the need for higher microwave power densities is increasing. One of the possibilities for improving power performances is to use new material systems. Group III-nitride materials are extremely attractive for high-power and high-temperature devices because of their intrinsic properties: large energy bandgap, high breakdown voltage, and high peak electron velocity. Microwave power devices such as AlGaN/GaN HEMTs have demonstrated impressive output power density greater than those of GaAs [1][2].

For microwave power HEMTs, a high current gain cut-off frequency along with a high saturation current is of essential importance. High drain current of 1,500 mA/mm with a transconductance of 300 mS/mm has been reported [3] with a classic modulation-doped HEMT structure. In this paper, we present and characterize a new delta-doped structure, including an AlN barrier. This structure, which aims to improve current carrying capabilities, exhibits high drain current and transconductance values close to the state of the art.

FABRICATION

The $Al_xGa_{1-x}N$/AlN/GaN heterostructures of this work are grown by low-pressure metalorganic chemical vapor deposition (MOCVD) in an EMCORE TurboDisc D125 UTM high-speed rotating-disk reactor on 2.0 in. diameter 4H semi-insulating SiC and 6H *n*-type SiC substrates. The AlGaN epitaxial layers are grown at pressures ~50 Torr and the GaN epitaxial layer is grown at ~200 Torr in a hydrogen ambient using adduct-purified trimethylgallium (TMGa), trimethylaluminum (TMAl), and ammonia (NH_3). The *n*-type dopant used was silane (SiH_4). A two-temperature growth process is employed with a high-temperature AlN buffer layer grown at ~1,070ºC and the high-temperature (HT) device layers grown at ~1,050ºC. In brief, the structure consists of a 100 nm AlN buffer layer, 3 µm undoped GaN, 1 nm AlN barrier layer, followed by a 30 nm $Al_xGa_{1-x}N$ (x~0.2) structure with delta doping after 5 nm of growth. Hall measurements taken at room temperature show a mobility of 1,058 cm^2/V·s and a sheet carrier density of 2.35×10^{13} cm^{-2}, yielding a large $n_s\mu$ product of 2.49×10^{16} /V·s.

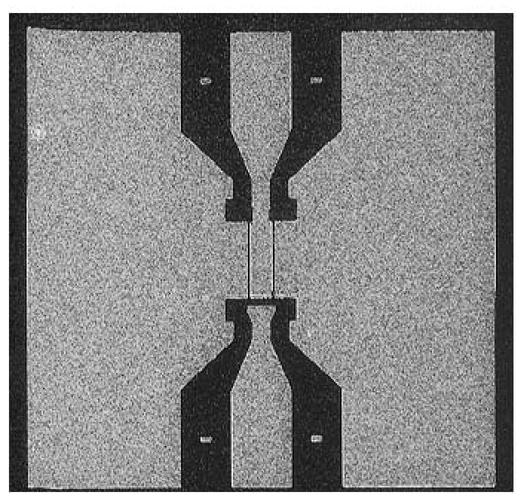

Figure 1. SEM micrograph of the HEMT device layout

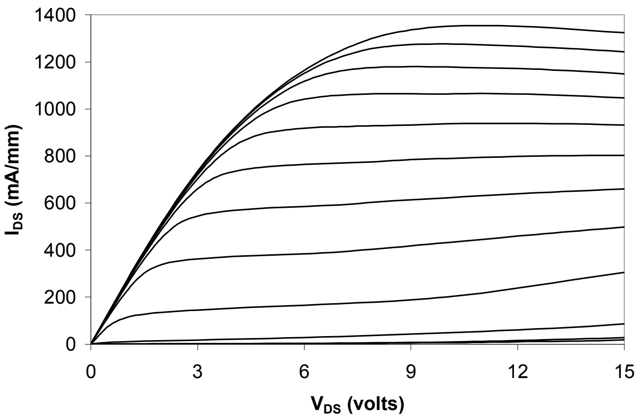

Figure 2. I_{DS}-V_{DS} characteristics of the AlGaN/AlN/GaN HEMT, with the gate bias ranging from +1 V to –10 V, in steps of 1.0 V

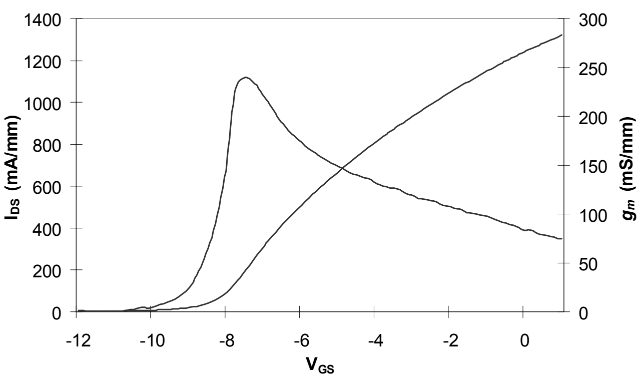

Figure 3. I_{DS} and g_m versus V_{GS} transfer characteristics, with V_{DS} = 15 V

The standard HEMT device in the GaN material system depends on the two-dimensional electron gas at the interface between AlGaN and GaN that is due to the large conduction band offset (ΔE_c) between the two materials, combined with the strong piezoelectric and polarization fields at the heterojunction interface. A thin AlN barrier layer can increase the effective conduction band offset to increase the sheet charge density without reducing the mobility [4]. In fact, the binary compound can also reduce the alloy scattering due to the AlGaN interface.

Devices are fabricated in a three-step process. Device isolation is achieved by dry etching with chlorine as the active species to a depth of 2,500 Å. Ohmic metal consisting of Ti/Al/Ti/Au is deposited in a lift-off process and alloyed by RTA at 950ºC. The 0.25-µm T-gate is defined by direct write e-beam using a tri-layer resist structure (5.5% PMMA/ 8.5% P(MMA-MAA) / 4% PMMA) at 40 kV and 1 nA. Ni/Au gates are deposited and the device is complete.

Experimental Results

The standard device tested is a 2×75 µm structure with parallel gate fingers (Fig. 1). DC results were obtained using an HP 4142B modular source unit. The I_{DS}-V_{DS} characteristics are shown in Figure 2, with the gate bias ranging from +1 V to –10 V, in steps of 1.0 V. The corresponding transfer characteristics can be seen in Figure 3, with the drain source voltage at 15 V. The peak transconductance is 240 mS/mm with a maximum current density of 1,320 mA/mm.

On-wafer high frequency measurements were made using an HP 8510C Network Analyzer. The probe station was equipped with 150-µm pitch Ground-Signal-Ground Pico microwave probes. The bias voltages were fed from the HP4142B dc source through bias-tees to the device under test. All the instruments were controlled by HP VEE software. S-parameters were measured from 250 MHz to 40.25 GHz. Off-wafer SOLT calibration was performed to move the reference planes as close as possible to the end of the probe tips. A built-in 12-term error model of the HP 8510C is used to calibrate the two-port network measurements. Values of f_t and f_{max} were obtained by extrapolating the magnitude of the current gain (h21) and the maximum available gain (U) to unity (Fig. 4). From the plot, f_t ~ 50 GHz and f_{max} ~ 130 GHz (as the extrapolated line follows a 6 dB/octave rolloff).

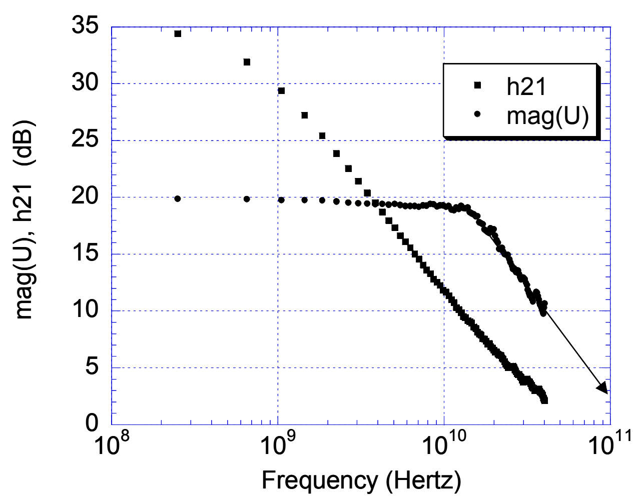

Figure 3. Plot of maximum available gain (U) and current gain (h_{21}) versus frequency. Extrapolated line shows a 6 dB/octave rolloff

Conclusions

Using an innovative AlGaN/GaN HEMT structure including a binary AlN barrier and an AlGaN delta-doped charge layer, a two-dimensional electron gas having a carrier mobility of μ_n = 1,058 cm^2/V·s and a sheet carrier density of n_s = 2.35×10^{13} cm^{-2} at room temperature were obtained, resulting in an $n_s\mu_n$ product of 2.49×10^{16} /V-s. AlGaN/GaN HEMT devices with 0.25 µm gate lengths exhibited maximum current densities as high as I_{DSmax} = 1.5 A/mm at V_G = 1 V and a peak transconductance of g_m = 240 mS/mm.

In addition, excellent high-frequency characteristics were measured with $f_t \sim 50$ GHz and $f_{max} \sim 130$ GHz.

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ACRONYMS

HEMT: High Electron Mobility Transistor
HP: Hewlett-Packard
MOCVD: Metalorganic Chemical Vapor Deposition
PMMA: Poly(Methyl Methacrylate)
RTA: Rapid Thermal Anneal
SOLT: Shorts, Opens, Loads, Thrus