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Research on GaN MODFET's

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Abstract

Initial results on 0.25 µm gate MODFET's have yielded f_t=21.4 GHz and f_{max}=77.5 GHz. These devices have characteristics that agree with the gradual channel model dominated by the electron mobility. The AlGaN/GaN structure, grown on sapphire substrates, are polycrystalline, and thus yield low mobility (<100cm ^{2}/Vs) at low electron sheet density. Using a simple model, design optimization predicts electron sheet density values of 7.3×10^{12} cm^{-2} in thin, 3 nm quantum wells for single-sided doping with 5 nm spacer for use in future high frequency $Al_{0.4}Ga_{0.6}N/In_{0.25}Ga_{0.75}N$/GaN MODFET's with gate lengths of 0.10 µm. Double sided doping with 5 nm spacers would yield a sheet density of 1.4×10^{13}cm^{-2} in such 3 nm quantum wells.

1. Introduction

Recent developments of III-V nitrides has extended their applications greatly in the areas of electrical devices as well as optical devices. The use of III-V nitrides on electrical devices is beneficial from their high breakdown voltages due to the wide band-gap, and high electron velocities. After the first demonstration of Heterojunction Field Effect Transistors (HFET's) on III-V nitrides [1], high power [2] and high frequency devices [3] have developed. Current state of the art transistors on III-V nitride materials have achieved transconductances of 120 mS/mm [4] or more and current densities in excess of 600 mA/mm [2]. For microwave devices, current gain cut-off frequency, f_t, of 32.1 GHz [5] and maximum oscillation frequency, f_{max}, of 77.5 GHz [6] have been reported utilizing 0.25 µm gate, and even higher f_t and f_{max} have been achieved [2]. Employing III-nitride layers, Metal-Semiconductor Field Effect Transistors [1] [7], Metal-Insulator Field Effect Transistors [7], and Modulation Doped Field Effect Transistors (MODFET's) have been fabricated.

2. Fabrication

The MODFET layers are grown by organometallic vapor phase epitaxy (OMVPE) on a (0001) Sapphire substrate. The grown layers are, from the bottom, an AlN buffer layer, thick (3-5 µm) GaN layer, 200 Å $Al_{0.16}Ga_{0.84}N$ layer, 75 Å GaN channel, 50 Å $Al_{0.16}Ga_{0.84}N$ spacer, 20 Å Si doped $Al_{0.16}Ga_{0.84}N$ charge supply layer, 130 Å $Al_{0.16}Ga_{0.84}N$ barrier, and 60 Å $Al_{0.06}Ga_{0.94}N$ cap layer. The charge supply layer and cap layer were Si-doped with a doping density of 2×10^{18} cm^{-3} (Figure 1) [6]. A Hall Measurement from Van der Pauw configuration showed a mobility of 680 cm^2/Vs and a sheet charge density of 7.3×10^{12} cm^{-2} at room temperature.

On the wafer, MODFET's were fabricated. Ni/AuSi/Ag/Au (100 Å/1000 Å/1000 Å/1500 Å) was used for ohmic contacts and was annealed at 750˚C for 30 s under N_2 atmosphere. The contact resistance was measured from a separate transmission line model (TLM) patterns to be 0.3 Ω mm. For the device isolation, proton (H^+) bombardment

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separate transmission line model (TLM) patterns to be 9.2 Ωmm. For the device isolation, proton (H^+) bombardment was used [1]. The penetration depth of protons was on the order of 1.0 μm. Electron-beam lithography was used to define 0.25 μm gates, and Ti/Pd/Au was employed as the gate metal. Before evaporating gate metals, the sample was cleaned with Buffered Oxide Etch to remove any oxides formed. Ti is known to have a Schottky barrier height of 0.58 eV on GaN from the measurement by Binari et al. [8]. The gate width of the MODFET's was 100 μm.

3. Measurements and Discussions

On fabricated MODFET's, DC characteristics as well as RF characteristics were measured. A drain current of 150 mA/mm was reached at 0 V gate bias (Figure 2a). The peak transconductance was 40 mS/mm (Figure 2b). The series source and drain resistances determined from the voltage divider measurement technique [9] were 14.6 Ωmm and 16.5 Ωmm respectively. The high contact resistances limited the device performance. The intrinsic transconductance calculated from the measured extrinsic conductances of 40 mS/mm was 96 mS/mm. From the gate length of 0.25 μm, the effective gate length can be calculated by adding twice the distance from gate to 2 dimensional electron gas. The calculated effective gate length is 0.31 μm. For the MODFET's, HP8510 network analyzer was used to measured S-parameters for the frequency range from 45 MHz to 26.5 GHz. The cutoff frequency, f_t, and maximum oscillation frequency, f_{max}, were determined from the current gain (h_{21}) and Mason's Unilateral gain (U), respectively. At a drain bias of 24 V, f_t of 21.4 GHz and f_{max} of 77.5 GHz were obtained (Figure 3). The increase of the drain bias caused the increase of f_t and f_{max} to a certain bias. This increase is currently believed to be from the composite effects of the increase of transconductance, according to the gradual channel model, and the decrease in the gate-drain capacitance, C_{gd}, with the drain bias increase as pointed out by Tasker et al [10].

A simple analytical method can be used to solve for the electron sheet density, N_s, in a full thin quantum well, using delta-doping, an $Al_{0.4}Ga_{0.6}N$ barrier with a minimum of 0.12 V above the Fermi energy, and 0.15 V ground state for electrons in the 30 Å $In_{0.25}Ga_{0.75}N$ channel. The following equations apply.

$$E_f \cong (1.052 - .12)\ V - \frac{2}{3}\Delta E_Q - \Delta E_s$$

where $\Delta E_Q = \left(\frac{N_s}{2a}\right)\frac{q}{\varepsilon_Q}\frac{(2a)^2}{2}$ and $\Delta E_s = N_s\left(\frac{q}{\varepsilon_s}\right)W_s$. all for single sided doping and

$$E_f = N_s / \left(88\times10^{12} / cm^2\ V\right) + 0.15\ V$$

In the equation ΔE_c=1.052 V, ($2a$)=3 nm, the thickness of the quantum well, ε_Q is the dielectric constant of the quantum well (12.77 ε_o), q is the electronic charge, W_s=5 nm, the thickness of the spacer layer, and ε_s is the dielectric constant in the spacer (11.0 ε_o). The quantum well state density is $88\times10^{12}/cm^2$-V. For this single-sided doping case, solving the equation yields $N_s \cong 7.3\times10^{12}\ cm^{-2}$. For double-sided doping, ΔE_Q is a quarter of the above, while ΔE_s is one half of the above. In this double-sided doping case, $N_s \cong 1.4\times10^{13}\ cm^{-2}$. ΔE_Q is the potential change in the quantum well, due to an assumed uniform charge density of $(N_s/2a)$, and ΔE_s is the potential change in the spacer layer due to the associated electron charge of qN_s for single-sided doping, or ($qN_s/2$) for double-sided doping. This simple solution assumes that there is a nearly constant potential in the quantum well, equal to $(2/3)\Delta E_Q$. The results of these simple calculations agree within ~10%, with the dedicated quantum mechanical solution of N_s.

4. Conclusion

A III-V nitride modulation doped field effect transistor structure was employed to fabricate FET's. The OMVPE grown wafer included a 75 Å GaN channel, a 50 Å $Al_{0.16}Ga_{0.84}N$ spacer and a 130 Å $Al_{0.16}Ga_{0.84}N$ barrier. The Si doped charge supplying layer was confined in 20 Å. The MODFET's were fabricated using proton bombardment for isolation, with Ni/AuSi/Ag/Au ohmic metal, and Ti/Pd/Au gate metal. The 0.25 μm × 100 μm gate devices yielded a maximum transconductance of 40 mS/mm and a drain current of 150 mA/mm at 0 V gate bias. RF results revealed f_t of 21.4 GHz and f_{max} of 77.5 GHz at the drain bias of 24 V. A simple analytical method can be useful in designing

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these structures to yield electron sheet density values.

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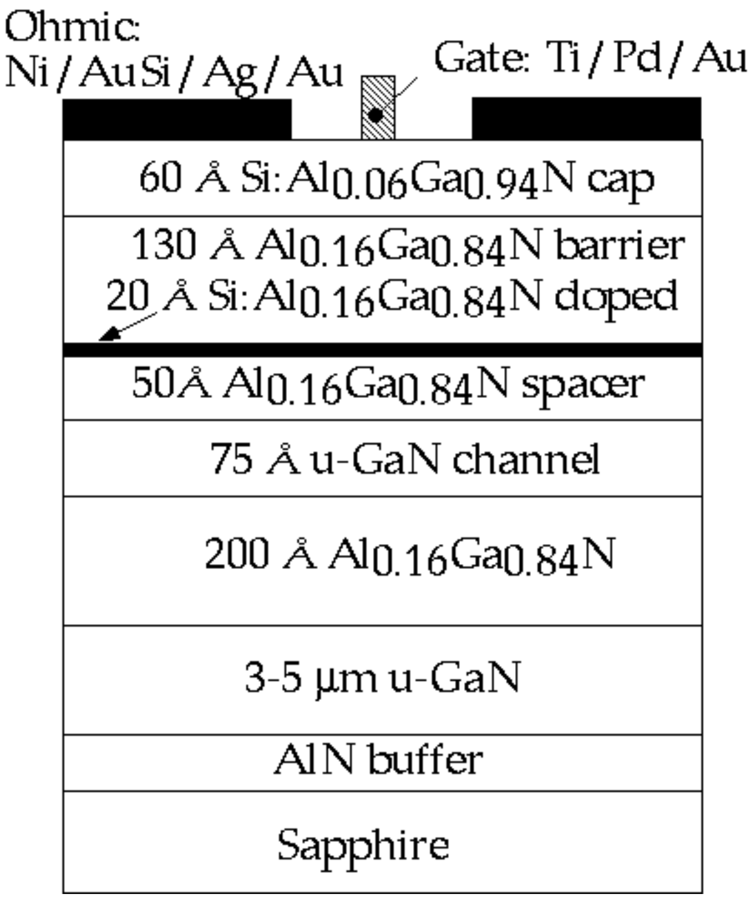

Figure 1. MODFET layer structure

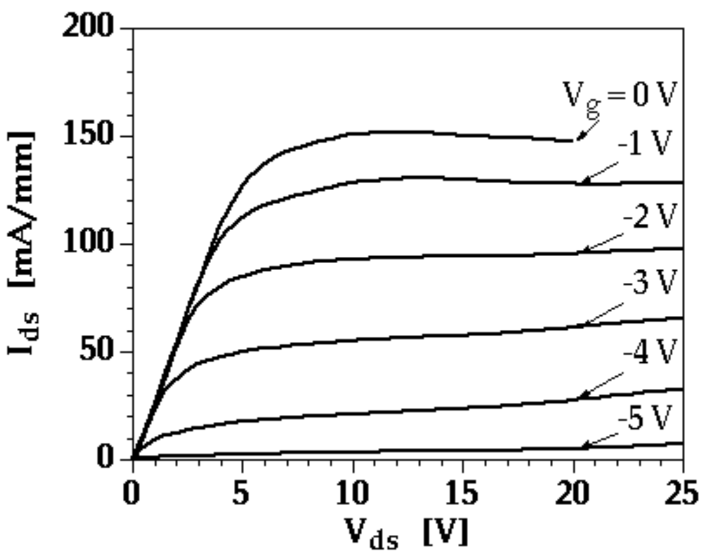

Figure 2a. Current-Voltage Characteristics of a MODFET.

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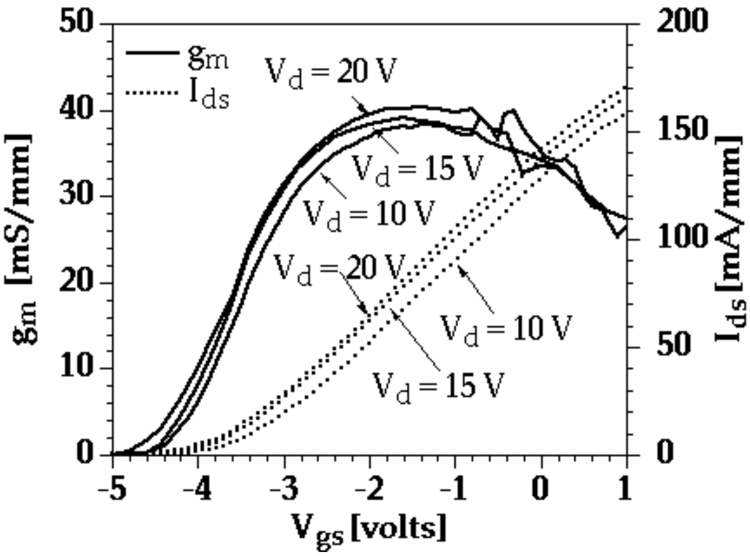

Figure 2b. Transconductance (g_m) and drain current (I_{ds}) of a MODFET.

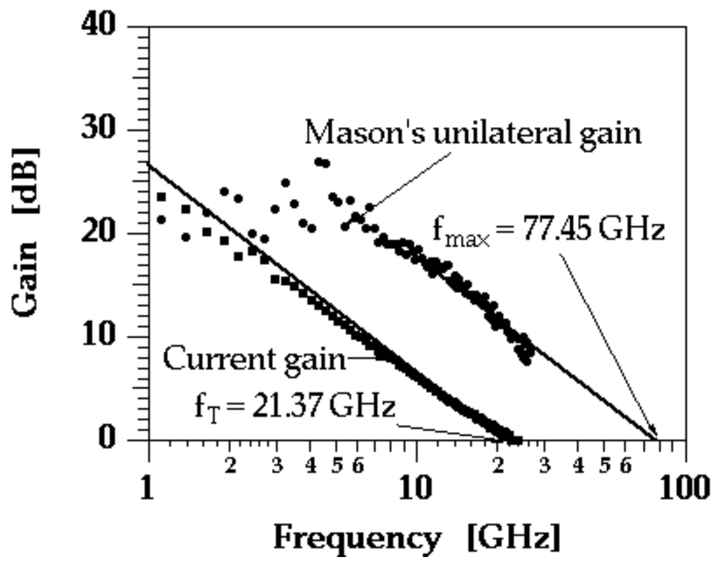

Figure 3. f_t of 21.4 GHz and f_{max} of 77 GHz was obtained at the drain bias of 24 V.

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