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Highly doped thin-channel GaN-metal–semiconductor field-effect transistors

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We report on the influence of the channel doping on dc, high frequency, and noise performance of GaN metal–semiconductor field-effect transistors (MESFETs) grown on sapphire substrates. The devices with the channel thicknesses from 50 to 70 nm and doping levels up to $1.5 \times 10^{18} \text{ cm}^{-3}$ were investigated. An increase in the channel doping results in the improved dc characteristics, higher cutoff, and maximum oscillation frequencies, and reduced low frequency and microwave noise. The obtained results demonstrate that the dc and microwave performance characteristics of short-channel GaN MESFETs may be comparable to those for conventional AlGaIn/GaN heterostructure FETs. © 2001 American Institute of Physics. [DOI: 10.1063/1.1344577]

GaN-based heterostructure field-effect transistors (HFETs) have emerged as a promising key building block for high power microwave electronics. Several groups demonstrated high power operation of AlGaIn/GaN HFETs at microwave frequencies,^{1–3} including a record-breaking result of 6.8 W/mm demonstrated by Cree, Inc. At Device Research Conference 2000, Cree, Inc. reported on incorporating an AlGaIn/GaN HFET into a hybrid amplifier that achieved 40 W of pulsed rf output power at 10 GHz. In the past, they have also reported on the monolithic microwave integrated circuit (MMIC) in GaN, grown on a semi-insulating SiC substrate. This GaN MMIC achieved 20 W of pulsed rf output power at 9 GHz, well exceeding the highest rf output power from AlGaAs/GaAs MMICs for this frequency range. Despite these impressive achievements, the conventional AlGaIn/GaN HFET device design suffers from several key problems, which impede the development of commercial AlGaIn/GaN HFETs:

- (i) the aging of HFETs, possibly due to traps caused by a partial relaxation of a large built-in strain at the AlGaIn–GaN heterointerface;
- (ii) drain current slump in a high power operation regime;
- (iii) large gate leakage in large periphery devices, caused by high doping of AlGaIn barrier layer (needed to reduce contact resistance). This leakage current leads to an excessive low- and high-frequency noise, which becomes a limiting factor for the applications of these devices in communication systems; and
- (iv) large source and drain contact resistance comparable with or even larger than the channel series resistance.

Recently, we reported on AlInGaIn/GaN metal–oxide–semiconductor HFETs (MOSHFETs) with SiO₂ insulating layer under the gate in the source-drain opening.^{4,5} This approach allowed us to fabricate devices with dc and rf char-

acteristics similar to those for conventional AlGaIn/GaN HFETs, however, with approximately 6 orders of magnitude lower gate leakage currents. Despite much lower gate leakage currents, the MOSHFET design has not yet solved the aging, current slump, and large contact resistance problems. New technical approaches and higher materials and AlGaIn/GaN heterointerface quality are required in order to eliminate the above problems. In this letter, we report on the performance of GaN-based thin channel highly doped metal–semiconductor field effect transistors (HDMESFETs). We demonstrate that these devices have a potential to compete with conventional AlGaIn/GaN HFETs, especially for short gate devices with moderate microwave powers.

In contrast to the GaN-based MESFETs reported by Khan *et al.*,^{6,7} Binari *et al.*,⁸ and, more recently, by Egawa *et al.*,⁹ our device design uses a higher doping level and a much thinner device channel. This design greatly enhances the device transconductance and reduces the parasitic source and drain resistances. Our calculations and experimental data show that short gate HDMESFETs have dc and rf performance similar to that of AlGaIn/GaN HFETs with added benefits of better stability and much smaller current slump.¹⁰

The structures were grown by low-pressure metalorganic chemical vapor deposition on (0001) sapphire substrates. The deposition of approximately 2 μm of nominally undoped GaN was followed by the growth of Si-doped GaN channel. The thickness and doping level of the channel were extracted from capacitance–voltage characteristics and varied from 50 to 70 nm and from 5×10^{17} to $1.5 \times 10^{18} \text{ cm}^{-3}$, respectively. The measured electron Hall mobility in the channel was close to $\mu = 100 \text{ cm}^2/\text{Vs}$.

The HDMESFETs with the source-drain spacing of 5 μm and the gate length of 1.5 μm were fabricated. Similar to our previously reported work, Ti/Al/Ti/Au ohmic and Ni/Au gate contacts were used. Figure 1 shows the HDMESFET dc and transfer characteristics. The measured maximum drain current was close to 300 mA/mm and the maximum trans-

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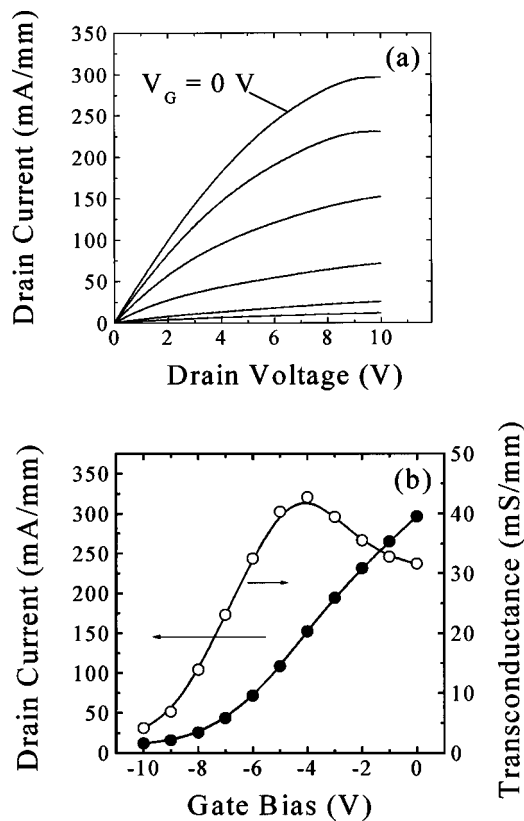


FIG. 1. Current–voltage (a) and transfer (b) characteristics of GaN HDMESFET with electron concentration in the channel $n = 1.5 \times 10^{18} \text{ cm}^{-3}$ and channel thickness of 70 nm.

conductance was 70 mS/mm. The gate turn-on voltage of the HDMESFETs was close to +1 V, which is approximately two times lower than for typical AlGaIn/GaN HFETs.¹¹ The source and drain contact resistances R_C were well below 0.5 Ω mm, which was less than the measured value for our AlGaIn/GaN and AlInGaIn/GaN HFETs.

The electron sheet density in our HDMESFETs with the channel thickness of 70 nm and the highest doping level of $1.5 \times 10^{18} \text{ cm}^{-3}$ was of the order of 10^{13} cm^{-2} . This is typical for the state-of-the-art AlGaIn/GaN HFETs. The electron Hall mobility of 100 $\text{cm}^2/\text{V s}$ in the HDMESFETs was an order of magnitude lower than 1000–1500 $\text{cm}^2/\text{V s}$ value for two-dimensional electrons in AlGaIn/GaN HFET heterostructures. However, the maximum saturation current in the HDMESFETs was only less by a factor of 3 from the best-reported values for AlGaIn/GaN HFET devices. These experimental data are in a good agreement with our simulation results shown in Fig. 2(a). These calculations use the MESFET model implemented in AIM-Spice.¹² As one can see from the figure, the difference in the saturation currents for the devices with high ($>1000 \text{ cm}^2/\text{V s}$) and low (100 $\text{cm}^2/\text{V s}$) electron mobility is much more pronounced for longer gates. For example, the saturation current in the low electron mobility devices with 1.5 μm gate is approximately 2.5 times lower than in the same geometry MESFETs with $\mu = 1200 \text{ cm}^2/\text{V s}$. The difference in the saturation current becomes less than 50% in the short channel devices with the gate length of 0.1 μm . The reason for this relatively small difference is that in short devices, the electron saturation velocity is a more important factor than a low-field mobility. These calculations do not account for possible velocity over-

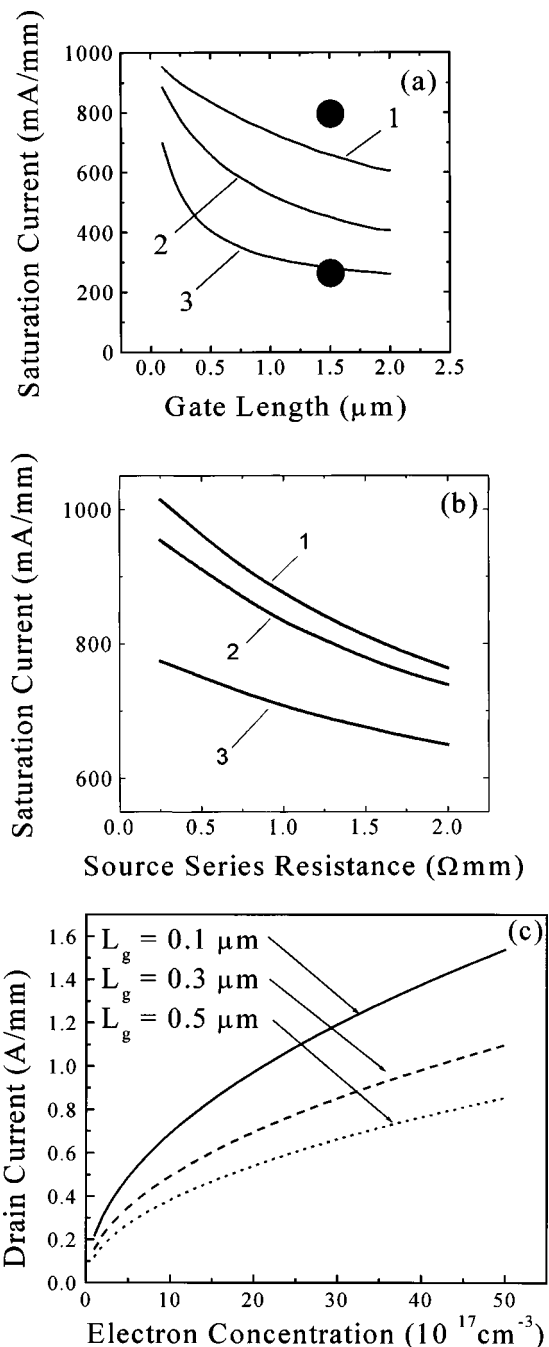


FIG. 2. (a) Calculated maximum drain current in GaN-based FETs with different electron mobility as a function of the gate length. Electron mobility for curve 1 is 1200 $\text{cm}^2/\text{V s}$, 2—400 $\text{cm}^2/\text{V s}$, 3—100 $\text{cm}^2/\text{V s}$. Solid dots show measured saturation currents in HDMESFETs (lower dot) and HFETs (upper dot) with similar threshold voltage. (b) Calculated maximum drain current in GaN-based FETs with different electron mobility as a function of the source series resistance. Electron mobility for curve 1 is 1200 $\text{cm}^2/\text{V s}$, 2—400 $\text{cm}^2/\text{V s}$, 3—100 $\text{cm}^2/\text{V s}$. Calculation results correspond to zero gate bias for the devices with the threshold voltage of $V_T = -6$ V and the gate length of 0.1 μm . (c) Calculated maximum drain current in GaN-based FETs with different gate length as a function of channel doping. Electron mobility in the channel, $\mu = 200 \text{ cm}^2/\text{V s}$. Calculations were performed for zero gate bias and taking threshold voltages of all devices as $V_T = -6$ V, and series resistance $R_S = 0.5 \Omega$ mm.

shoot effects in GaN-based transistors. If and when these effects are important, the effect of the low-field mobility will be still smaller. Also, the source and drain series resistances are relatively more important in devices with shorter gates. In these simulations, we assumed that while the electron mobility in the channel changes, the series resistance of the

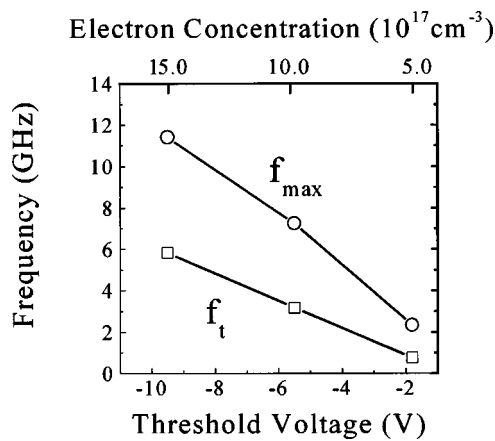


FIG. 3. Cutoff frequency f_t and maximum oscillation frequency f_{max} for GaN HDMESFETs with different channel doping. Threshold voltage $V_T = -1.8$ V corresponds to the electron Hall concentration in the channel $n = 5 \times 10^{17} \text{ cm}^{-3}$; $V_T = -5.5$ V to 10^{18} cm^{-3} ; $V_T = -9.5$ V to $1.5 \times 10^{18} \text{ cm}^{-3}$.

source-gate opening remains nearly constant ($0.5 \text{ } \Omega \text{ mm}$). In practical designs, this can be achieved by using either an ion implantation technique or a recessed gate approach. However, our simulations [see Fig. 2(b)] also showed that even at higher source series resistances (up to $2 \text{ } \Omega \text{ mm}$) GaN HDMESFETs remain competitive with AlGaIn/GaN HFETs.

Figure 2(c) shows the effect of channel doping on MESFET saturation current (at zero gate bias). In these simulation, the electron mobility in the channel was kept constant, $\mu = 200 \text{ cm}^2/\text{V s}$. The source-gate series resistance, $R_s = 0.5 \text{ } \Omega \text{ mm}$, as in Fig. 2(a). As seen, the submicron gate devices with highly doped channel demonstrate a very high saturation current, which is comparable to that of HFETs.

Figure 3 shows the cutoff frequency f_t and maximum oscillation frequency f_{max} for GaN HDMESFETs with different channel doping concentrations and, hence, different threshold voltages. As seen from Fig. 3, an increase in the doping by a factor of 3 results in approximately 5 times higher cutoff frequencies and almost 8 times higher maximum oscillation frequencies for the HDMESFETs. The maximum cutoff frequency times the gate length product is as high as $11.6 \text{ GHz } \mu\text{m}$. The measured maximum f_t and f_{max} values are comparable with identical geometry conventional AlGaIn/GaN HFETs and MOSHFET devices.⁴

Microwave power performance of the $200 \text{ } \mu\text{m}$ wide GaN HDMESFETs with channel doping of $1.5 \times 10^{18} \text{ cm}^{-3}$ at 2 GHz was investigated in continuous wave (cw) and pulsed measurement regimes. The pulsed rf was measured using $20 \text{ } \mu\text{m}$ drain voltage pulses with time between pulses 7.8 ms. The output powers were 0.6 W/mm and 3.4 W/mm for the cw and pulsed operation, respectively. These measured microwave power is comparable with those for conventional AlGaIn/GaN HFETs. These can further be increased by using better thermal management for a more efficient heat removal. Our preliminary data show a much more stable microwave power performance and significantly lower current slump for the HDMESFETs as compared to AlGaIn/GaN HFETs. The results of this study will be published elsewhere.

TABLE I. Low frequency and microwave noise data for GaN MESFETs.

Channel doping, cm^{-3}	Hooge parameter	Microwave noise/ associated gain
5×10^{17}	2×10^{-2}	$F_{\text{min}} = 4.2 \text{ dB}$ -0.45 dB
10^{18}	3×10^{-3}	$F_{\text{min}} = 3.2 \text{ dB}$ 0.85 dB
1.5×10^{18}	2×10^{-3}	$F_{\text{min}} = 1.5 \text{ dB}$ 4.5 dB

An increase in the channel doping also improved both low frequency and microwave noise performance of the HD-MESFETs. The low frequency noise is found to be of $1/f$ character with Hooge parameter strongly dependent on the channel doping. The results of the noise measurements are summarized in Table I. The devices with the highest channel doping exhibited the best noise performance. The extracted values of Hooge parameter were close to 10^{-3} , which is comparable to the state-of-the art AlGaIn/GaN HFETs.

In conclusion, we demonstrated a high performance GaN HDMESFETs with a heavily doped thin channel design. The devices exhibited microwave power and noise performance characteristics comparable to those of AlGaIn/GaN HFETs with a similar geometry. Our data show that dc characteristics and high power performance of short gate HDMESFETs with improved material quality (electron mobility close to $200 \text{ cm}^2/\text{V s}$) can be comparable to AlGaIn/GaN HFETs. In addition, the HDMESFETs are expected to have a much better stability (less pronounced aging), which is crucial for device applications in advanced microwave and millimeter wave systems.

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