High-power SiO_2/AlGaN/GaN metal-oxide-semiconductor heterostructure field-effect transistors

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We report on SiO_2/AlGaN/GaN metal-oxide-semiconductor heterostructure field-effect transistors (MOSHFETs), which exhibit a 6.7 W/mm power density at 7 GHz. Unpassivated and SiO_2-passivated heterostructure field-effect transistors (HFETs) were also investigated for comparison. Deposited 12 nm thick SiO_2 yielded an increase of the sheet carrier density from 7.6×10^{12} to 9.2×10^{12} cm^{-2} and a subsequent increase of the static drain saturation current from 0.75 to 1.09 A/mm. The small-signal rf characterization of the MOSHFETs showed an extrinsic current gain cutoff frequency f_T of 24 GHz and a maximum frequency of oscillation f_{max} of 40 GHz. The output power of 6.7 W/mm of the MOSHFETs measured at 7 GHz is about two times larger than that of HFETs. The results obtained demonstrate the suitability of GaN-based MOSHFETs for high-power electronics. © *2005 American Institute of Physics*.
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GaN-based metal-insulator-semiconductor heterostructure field-effect transistors (MISHFETs) have recently been under study mainly because they suffer from lower gate leakage currents compared with simple heterostructure field-effect transistors (HFETs). The application of various insulators, such as SiO_2,[1–3] SiN,[3–5] Al_2O_3,[6,7] AlN,[8] and AlON,[9] was reported. Mainly, only the static performance of MISHFETs has been investigated, and the preference of an insulator type has not been defined yet. Silicon nitride was originally proposed as the passivation layer of AlGaN/GaN HFETs,[10] and a density of interface states about ten times lower than that for SiO_2 on GaN was found.[11] Published data on AlGaN/GaN MISHFETs with SiN or SiO_2 insulator do not show a significant difference in their static performance. Small-signal microwave characterization of metal-oxide-semiconductor HFETs (MOSHFETs) with SiO_2 yielded a current gain cutoff frequency f_T of 8.2 GHz (see Ref. 1) and 9.5 GHz (see Ref. 2) on 2 μm and 1 μm gate length devices, respectively. Recently, we reported an f_T of 24 GHz and f_{max} of 40 GHz for SiO_2/AlGaN/GaN MOSHFETs.[12] On the other hand, f_T of 63 GHz and f_{max} of 64 GHz were extracted for Si_3N_4-based MISHFETs with 0.25 μm gate length.[5] These small-signal data are comparable to those typical for the state-of-the-art AlGaN/GaN HFETs. The large-signal performance of MISHFETs is less reported. An output power density of 4.2 W/mm at 4 GHz (see Ref. 4) and 5 W/mm at 10 GHz,[5] in both cases about two times larger than that for unpassivated HFETs, was found on Si_3N_4-based MISHFETs. However, highly efficient SiO_2-based AlGaN/GaN MOSHFET capacitors with 60 W/mm switching power at 2 GHz have been recently demonstrated.[13] All of this indicates that the question of a preferable insulator for AlGaN/GaN MISHFETs is still open. It can be expected that the quality of an insulator used, that is, its preparation conditions, will be the key factor in the optimization of their performance.

In this letter, we report on the static and microwave performance of AlGaN/GaN MOSHFETs with a SiO_2 insulator. For comparison, the performance of unpassivated and SiO_2-passivated HFETs, processed simultaneously on similar material structure, is presented as well. It is shown that SiO_2-based MOSHFETs exhibit an output power of 6.7 W/mm at 7 GHz, which is about 50% higher than that measured on the passivated HFET counterparts.

The material structure for all devices reported here consisted of 3 μm undoped GaN and a 30 nm undoped $Al_{0.28}Ga_{0.72}N$ layers grown on insulating 4H–SiC substrate by low-pressure metalorganic chemical vapor deposition (Cree-GaN Durham). The device processing consisted of conventional FET fabrication steps. At first, mesa etching isolation using argon sputtering was performed. After that, ohmic contacts were prepared by evaporating multilayered Ti/Al/Ni/Au system followed by rapid thermal annealing at 850 °C for 30 s in a N_2 ambient. An ohmic contact resistance of 0.22–0.35 Ω mm was measured using the transmission-line method. A SiO_2 layer of 10 nm nominal thickness was deposited by plasma-enhanced chemical vapor deposition between the source and drain contacts. The Schottky gate metallization consisted of a Ni/Au double-layer patterned by e-beam lithography. Devices with a gate length of 0.3–0.9 μm and a gate widths of 100 μm and 200 μm (two fingers) were prepared. Van der Pauw patterns with an active area of 0.3×0.3 mm^2 were processed simultaneously with the HFET devices. To prepare passivated HFET counterparts, the same SiO_2 deposition procedure was applied after gate metallization. Unpassivated HFETs were also prepared on the same material structure.

The material structure was characterized by Hall effect measurements on van der Pauw patterns and *C-V* measurements on HFET devices as well. The Hall effect data yielded

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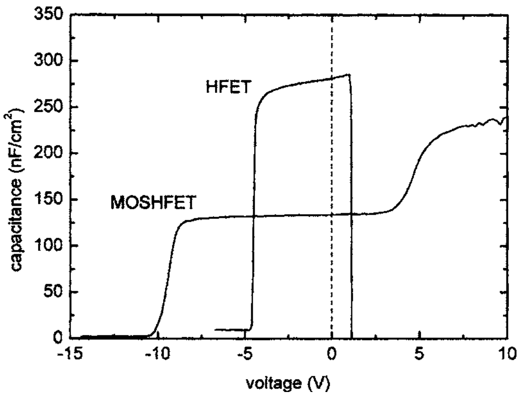

FIG. 1. Capacitance-voltage characteristics of a SiO_2/AlGaN/GaN MOSHFET and AlGaN/GaN HFET.

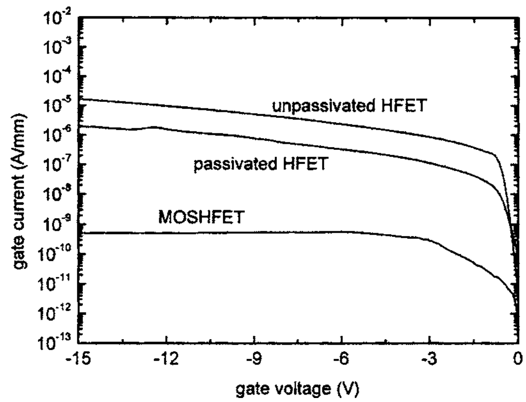

FIG. 2. Two terminal gate-source *I-V* characteristics of SiO_2/AlGaN/GaN MOSHFET and AlGaN/GaN HFETs before and after passivation.

a sheet carrier density of 7.14×10^{12} and 9.25×10^{12} cm^{-2} and carrier mobilities of 1835 and 1670 cm^2/V s on unpassivated and SiO_2-passivated material structures, respectively. The passivation-induced sheet carrier density $\Delta n_s=2.1\times10^{12}$ cm^{-2} and a partial decrease of the mobility are in good agreement with our previous investigations ($\Delta n_s=1.5\times10^{12}$ cm^{-2} after Si_3N_4 passivation).[14] Figure 1 shows the capacitance-voltage characteristics typical for a MOSHFET and unpassivated HFET. The *C-V* curves show sharp transitions and negligible hysteresis. The sheet carrier densities of 7.6×10^{12} cm^{-2} and 9.2×10^{12} cm^{-2} evaluated from the capacitance and threshold voltage for HFET and MOSHFET, respectively, are in good agreement with the Hall data. The AlGaN thickness $d_{AlGaN}=\varepsilon/C_0=29.4$ nm follows from the zero-bias capacitance of HFET, comparing to the nominal thickness of 30 nm. Considering that $C_{HFET}/C_{MOSHFET}=[1+(d_{SiO_2}/d_{AlGaN})(\varepsilon_{AlGaN}/\varepsilon_{SiO_2})]$ and using AlGaN and SiO_2 layer permittivities $\varepsilon=9.2$ and 3.9, respectively, a SiO_2 thickness of 12 nm is obtained. The nominal thickness of SiO_2 was 10 nm. A saturation of the MOSHFET capacitance at higher gate voltages indicates that the capacitance of only the SiO_2 insulator was measured. Our preliminary evaluation of the single-frequency capacitance and conductance data indicates that the SiO_2/AlGaN interface state density is $D_i\cong1.1\times10^{12}$ cm^{-2} eV^{-1}. This is in good agreement with results published before on SiO_2/GaN structures, in spite of about a ten times lower D_i found for the SiN/GaN interface.[11]

The existence of high gate leakage current is a well known problem of AlGaN/GaN HFETs. It can be partially suppressed if passivation is used. Another alternative is an enhancement of the Schottky barrier height by an undoped GaN cap on top of the heterostructure: a gate leakage current of about 10^{-8} A/mm was found on unpassivated devices.[15] However, structures with a gate insulator show an even smaller gate current, as is actually known from the literature. Figure 2 shows a comparison of typical two terminal gate-source *I-V* characteristics for HFET before and after passivation and for a MOSHFET as well. The gate current of $\sim5\times10^{-10}$ A/mm at $V_G\leqslant-6$ V was measured on the SiO_2/AlGaN/GaN MOSHFET. This is a lower value than is typically reported for MISHFETs with various insulators. On the other hand, it should be noted that according to recent findings, a SiO_2 gate insulator suffers a lower gate current than Si_3N_4; a current of about 1×10^{-10} A/mm was presented.[3]

The static output characteristics of prepared MOSHFETs yielded a maximum drain current density of 1.09 A/mm at $V_G=1$ V and a pinch-off voltage of about -11 V. The maximum drain current of HFETs increased from 0.77 to 0.92 A/mm after passivation. The peak extrinsic transconductance $g_m\cong120$ mS/mm was measured for MOSHFET, as compared to 170 and 184 mS/mm for unpassivated and passivated HFETs, respectively (Fig. 3). The reduction of g_m for the MOSHFET follows from a larger separation of the channel from the Schottky contact. However, a broader transconductance profile should provide a larger gate voltage swing and thus improve the large-signal microwave conditions. Small-signal characterization of the MOSHFETs with 0.7 μm and 200 μm gate length and width, respectively, yielded an extrinsic current gain cutoff frequency f_T of 24 GHz and a maximum frequency of oscillation f_{max} of 40 GHz, biased at peak g_m.[12] These are fully comparable values with those reported on the state-of-the-art AlGaN/GaN HFETs.

Microwave power measurements were performed using an on-wafer load pull measurement system. Output power sweeps of the devices were conducted at 7 GHz. Impedance matching was accomplished with automatically adjusted tuners. The devices were biased to a V_G, V_D point which corresponds to the class A operation. The output power P_{out}, gain G, and power-added efficiency PAE as a function of the input power P_{in} were measured. The peak output power density for various drain biases on samples investigated is shown in Fig. 4. An advantage of the AlGaN/GaN MOSHFET over HFET

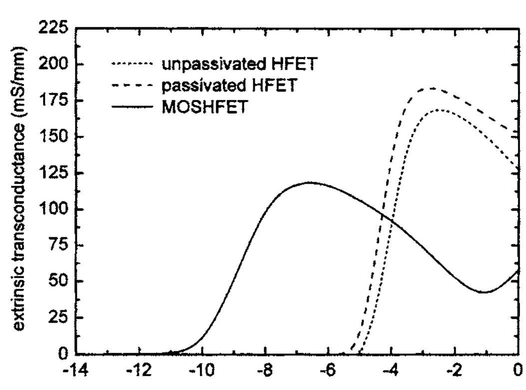

FIG. 3. Extrinsic transconductance for a MOSHFET, and unpassivated and passivated HFETs (the gate length is 0.7 μm).

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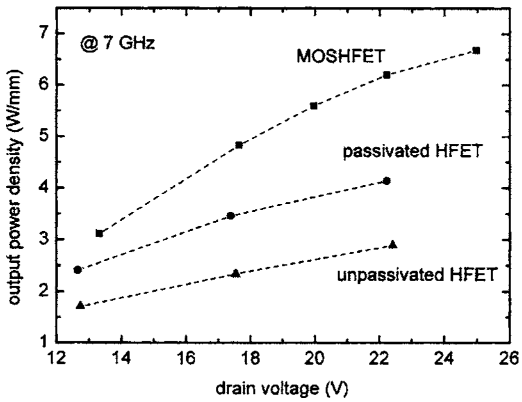

FIG. 4. Output power density at 7 GHz for a MOSHFET and unpassivated and passivated HFETs measured at various drain biases on devices with 0.7 μm and 200 μm gate length and width, respectively. The dashed lines are guides for the eye.

is demonstrated clearly. The peak output power density P_{in} $=6.7$ W/mm at 25 V drain bias was measured on a MOSHFET with a 200 μm gate width. This is a higher value than that reported before on devices with a Si_3N_4 gate insulator.[4,5] This result documents a good quality of the SiO_2 insulator used, and a very low drain current dispersion of the device. The output power of the MOSFET is about 50% larger than the power of a passivated HFET at the same drain bias. This indicates that the insulator below the gate reduces not only the gate leakage current but also the drain current collapse. Further improvement in the output power of MOSHFETs can be expected using a field-plated device design, which has been applied on HFETs.[16] Such experiments are in progress.

In summary, the static, small-signal, and microwave power performance of AlGaN/GaN MOSHFETs with a SiO_2 insulator was described. Unpassivated and SiO_2-passivated HFETs, processed simultaneously on similar material structure, were investigated for comparison, too. The present MOSHFETs exhibit favorable characteristics when compared to HFETs. The gate leakage current of 5×10^{-10} A/mm is about four orders of the magnitude lower than that of HFETs. The saturation drain current increased from 0.77–0.92 A/mm for HFETs to 1.09 A/mm for the MOSHFET. Microwave power measurements at 7 GHz yielded an output power of 6.7 W/mm, which is about two times larger than that of HFETs. These characteristics imply excellent potential of the SiO_2/AlGaN/GaN MOSHFETs for high-power microwave applications.

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