12 GHz F_{MAX} GaN/AlN/AlGaN Nanowire MISFET

Simon Vandenbrouck, Kamel Madjour, Didier Théron, *Member, IEEE*, Yajie Dong,
Yat Li, Charles M. Lieber, and Christophe Gaquiere

***Abstract*—GaN/AlN/AlGaN/GaN nanowire metal–insulator–semiconductor field-effect transistors (MISFETs) have been fabricated for the first time with submicrometer gate lengths. Their microwave performances were investigated. An intrinsic current-gain cutoff frequency (F_T) of 5 GHz as well as an intrinsic maximum available gain (F_{MAX}) cutoff frequency of 12 GHz have been obtained for the first time and associated with a gate length of 0.5 μm. These results show the great potentiality of GaN-based nanowire FETs for microwave applications.**

***Index Terms*—Heterojunction, metal–insulator–semiconductor FET (MISFET), microwave field-effect transistors (FETs), quantum wires, semiconductor devices.**

I. Introduction

GaN is a very attractive semiconductor. It has allowed a revolution in the field of blue and white light-emitting diodes as well as for microwave power applications. This is mainly due to its large band gap that is more than tripled as compared to silicon and more than doubled as compared to GaAs. GaN allows the realization of AlGaN/GaN heterostructures. This heterojunction contains an internal polarization field that induces the presence of a 2-D electron gas without intentional doping. High breakdown voltages, electron mobilities, and carrier densities can be achieved, which have allowed the realization of microwave amplifiers with record power [1]–[3]. GaN nanowires are therefore of strong interest, since we expect to benefit of these properties at the nanoscale and use them as future building blocks for a wide range of optical, electrical, or chemical applications.

The transport properties of single GaN nanowires grown by thermal catalytic chemical vapor deposition have already been studied. The as-grown GaN nanowires exhibited n-type conductivity with an electron density of about 2×10^{17} cm^{-3} and a mobility of 30 cm^2/V $\cdot$ s [4]. In [5] and [6], n- and p-type GaN nanowire field-effect transistors (FETs) have also been investigated. However, up to now, all these studies demonstrated only static electrical measurements, and to our knowledge, GaN nanowire-based FETs have never been studied in microwave regime. In this letter, we demonstrate for the first time the fabrication of submicrometer gate AlGaN/GaN heterojunction metal–insulator–semiconductor FETs (MISFETs) and their characterization at microwave frequencies on a dedicated layout, showing a promising breakthrough for future high-frequency downscalable logic circuit, sensors, and RF applications.

II. GaN Nanowire Growth

Nanowires were synthesized on a c-plane sapphire substrate in a metal–organic chemical-vapor-deposition reactor (Thomas Swan Scientific Equipment, Ltd.) using trimethylgallium (TMG), trimethylaluminum (TMA), and ammonia (NH_3) as Ga, Al, and N sources, respectively, and nickel nanoclusters as core-growth catalysts. GaN cores were grown in hydrogen at 775 °C and 100 torr for 7500 s using TMG (22 μmol/min) and NH_3 (58 mmol/min). For this condition, the GaN core nanowires were 80–160 nm in diameter and 10–20 μm in length. Subsequently, the growth conditions were altered to favor AlN and AlGaN shell growth. The shell growth was carried out in constant NH_3 flow (180 mmol/min) in hydrogen at 50 torr and 1040 °C. An AlN shell was first deposited for 18 s using TMA (13 μmol/min) and AlGaN shell for 80 s using TMA (13 μmol/min) and TMG (44 μmol/min). The core/shell/shell were characterized by conventional and cross-sectional transmission electron microscopy (TEM) as described previously. Other information concerning these NWs has already been published [6].

III. GaN MISFET Fabrication

The dopant-free GaN/AlN/AlGaN radial nanowires used for the fabrication of the AlGaN/GaN heterojunction MISFETs have a high mobility, typically in the range of 3100 cm^2/V $\cdot$ s at room temperature [6]. The Al content in AlGaN is 25%. The NWs were randomly transferred with a dry-transfer method onto a sapphire substrate by reporting the growth substrate onto a clean sapphire substrate and then applying a smart pressure. This substrate was chosen for two reasons. First, we need a tough material to avoid scratches made by the NWs during the transfer. Second, the high-resistivity sapphire is convenient for microwave characterization of devices, which requires low-loss substrates.

After the transfer of NWs, the device fabrication is performed, and it consists of four steps. Ti/Al/Ni/Au was first deposited for the ohmic contacts. They were formed by annealing at 900 °C for 30 s. Then, the whole wafer was covered by a SiN_x dielectric layer deposited by PECVD at 340 °C. The SiN_x dielectric thickness is 20 nm. Then, the Mo/Au gate metal stack was deposited on the dielectric layer. Finally, after SiN_x local

Manuscript received September 26, 2008; revised January 23, 2009. Current version published March 25, 2009. This work was supported in part by the University of Lille under Grant PPF 20061800 and in part by the Conseil Regional Nord Pas de Calais. The review of this letter was arranged by Editor G. Meneghesso.

S. Vandenbrouck, K. Madjour, D. Théron, and C. Gaquiere are with the Institute of Electronics Microelectronics and Nanotechnologies, UMR Centre National de la Recherche Scientifique 8520, 59652 Villeneuve d'Ascq, France (e-mail: simon.vandenbrouck@iemn.univ-lille1.fr).

Y. Dong, Y. Li, and C. M. Lieber are with the Department of Chemistry and Chemical Biology, Harvard University, Cambridge, MA 02138 USA.

Digital Object Identifier 10.1109/LED.2009.2014791

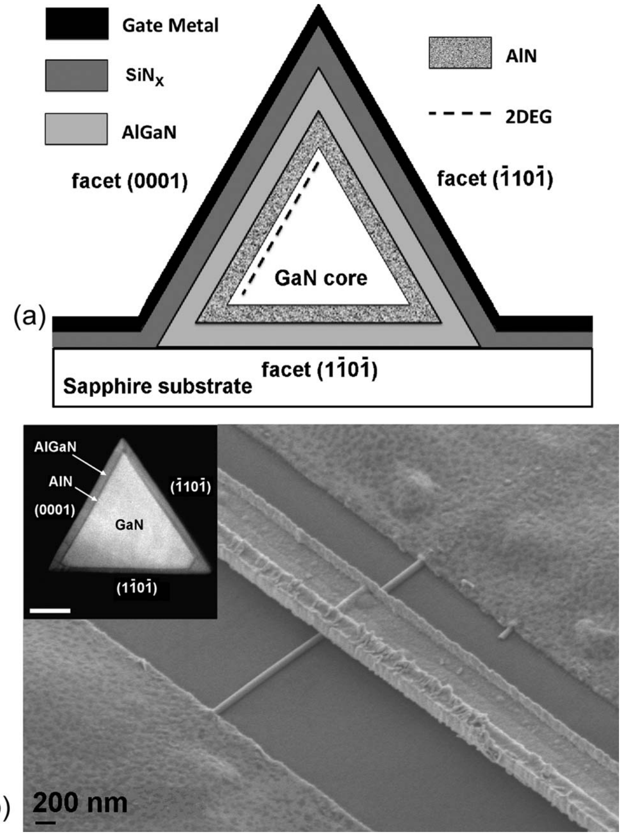

Fig. 1. (a) Schematic cross section of an NW covered by SiN_x and the gate. (b) (Main frame) SEM photography showing an NW connected between the source and drain. (Inset) TEM image of a GaN/AlN/AlGaN NW cross section. Scale bar is 50 nm [6].

removal, the coplanar access lines were deposited over the gates and ohmic contacts, allowing the microwave characterization with standard 50-Ω equipment. All metal layers were deposited by e-beam evaporation. The SiN_x layer under the gate has been intentionally deposited in order to avoid gate leakage that was observed without it and was attributed to the gate contact on the (-110-1) or (1-10-1) facets assuming a reduced Schottky barrier height and the potential presence of a 2-D hole gas as an electrical-conduction path.

With this method, devices with different numbers of nanowires were realized as well as passive structures with no GaN nanowire. The device structures present two-finger gates, with a unitary gate finger width of 150 μm.

The nanowire facets are 80 nm wide and oriented along the (0001), (-110-1), and (1-10-1) planes [6]. As the spontaneous and piezoelectric field orientation is perpendicular to the (0001) face, only that plane will form a conduction band well, and the two other facets will form a valence band well [7]. However, even if a hole gas might be present, the N type of the ohmic contact will selectively contact electrons, which explains the electron-type conduction of the device. We may thus consider that the channel is confined at the (0001) facet. Concerning gate-charge control, it may change according to the fact that the (0001) facet may be in contact with the gate or the substrate [Fig. 1(a)], but, as a first approach, we considered that the gate is above the (0001) face and that the gate width is that of one facet (i.e., 80 nm).

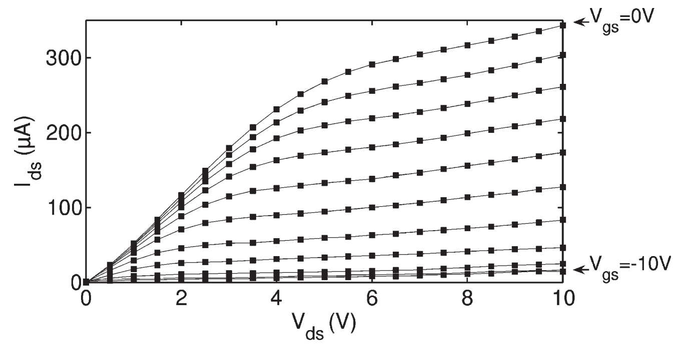

Fig. 2. Drain–current versus drain-to-source voltage of a GaN/AlN/AlGaN NW MISFET. V_{gs} varies from 0 to -10 V with a step of 1 V.

The drain-source spacing is 3 μm ($\mathrm{L_{gs}} = 1\ \mu\mathrm{m}, \mathrm{L}_g = 0.5\ \mu\mathrm{m}, \mathrm{L_{gd}} = 1.5\ \mu\mathrm{m}$). Fig. 1(b) shows a SEM photography of an NW connected between drain and source ohmic contacts.

IV. Characterization

A. Static Characterization

DC characterization was performed using Agilent Technologies E5273A power supplies, controlled with the ICCAP software. Fig. 2 shows the output drain–current (I_D) versus drain-source voltage (V_{DS}) characteristics for several gate–source voltages. A maximum current of 350 μA is obtained. Five NWs connected between source and drain contacts have been counted on this device. Therefore, a mean current of 70 μA for each wire can be estimated, which leads to an estimated current density of about 0.87 A/mm. This value is much better than the previously published results of 8 μA per wire [6]. This is attributed to an improvement in our gate process and, in particular, in the dielectric layer located between the gate and the nanowire. A -8.5-V pinch-off voltage is calculated from the following equation: $V_t = (\Phi_B - \Delta E_C)/q - \sigma_{\mathrm{int}}\ \ (d_{\mathrm{AlGaN}}/\varepsilon_0\varepsilon_{\mathrm{AlGaN}} + d_{\mathrm{SiN}}/\varepsilon_0\varepsilon_{\mathrm{SiN}})$, where $\Phi_B = 0.8$ eV is the Schottky barrier height, $\Delta E_C = 0.53$ eV is the conduction-band discontinuity between AlGaN and GaN, $\varepsilon_0\varepsilon_{\mathrm{AlGaN}} = 8.85\times10^{-12}\times9.35\ \ (\varepsilon_0\varepsilon_{\mathrm{SiN}} = 8.85.10^{-12}\times7.5)$ is the dielectric constant of AlGaN (SiN_x), $d_{\mathrm{AlGaN}} = 10$ nm ($d_{\mathrm{SiN}} = 20$ nm) is the AlGaN (SiN_x) layer thickness, $\sigma_{\mathrm{int}} = 1.3\times10^{13}\ \mathrm{cm}^{-2}$ is the interface charge related to the polarization field discontinuity, and q is the elementary electric charge. The measured value of -8 V fits the theory and confirms the good orientation of the wires for this device.

Because of the wide band gap of GaN, the breakdown voltage is expected to be high. Although we did not investigate this point since we had few working devices, a 10-V drain-source voltage could be applied without electrical limitations, which allowed us in obtaining a clear transition between the ohmic and the saturated behaviors. This opens a large area of microwave electrical applications.

In Fig. 3, the dc drain–current and transconductance dependences versus gate voltage (V_{GS}) are shown for a drain-source voltage of 10 V. The transconductance reaches 45 μS and shows an excellent flatness. Using the same assumption as for drain–current, we can estimate the transconductance to be 78 mS/mm. This moderate but still good value as compared

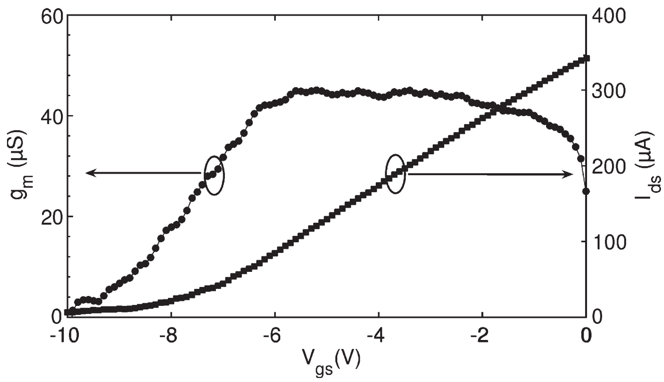

Fig. 3. Transconductance and drain–current of the device versus gate voltage V_{GS} at $V_{DS} = 10$ V.

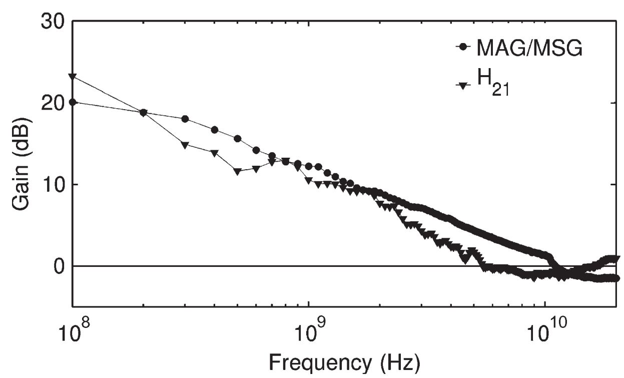

Fig. 4. Intrinsic maximum stable and maximum available gain and intrinsic current gain versus frequency. $V_{DS} = 10$ V. $V_{GS} = -4$ V.

with conventional HEMTs is attributed to the presence of the insulating SiN_x layer between the gate and the AlGaN/GaN heterojunction that reduces the gate-control efficiency. It shows a strong improvement with the previously published results of 2.4 μS per wire [6].

B. Microwave Characterization

The CW scattering (S) parameters were measured with microwave probes using an Agilent E8361A PNA Network Analyzer. The measurements were performed in the 0.5–67-GHz frequency range for different bias conditions. An LRM calibration procedure of the network analyzer allows us in defining the measurement reference planes at the probe tips. In order to remove the access lines from the probe to the active NW area, dedicated passive structures (same topologies but without NWs) were used. These S parameters were subtracted from the whole device S parameters after transforming them into Y parameters using de-embedding [8].

From these measurements, we determine the intrinsic current gain $(|H_{21}|^2)$ for $V_{DS} = 10$ V and $V_{GS} = -4$ V. The results (Fig. 4) show a cutoff frequency of 5 GHz. Due to their nanoscale, the output conductance of the GaN nanowire devices is very low ($\sim$0.01 mS), which results in a high mismatch between the FET output impedance and the 50-Ω VNA setup. Therefore, the S_{22} parameter is near one. The de-embedding procedure leads to the subtraction of very reflective elements (mainly capacitances), leading to values that are not far from the noise of the measurement setup, which induces some fluctuations of the current gain that have been partly smoothed in the figure. The measurement accuracy will be improved by increasing the number of NWs connected, which will reduce at the same time the FET impedance and the influence of the parasitic elements. We determine also the maximum stable gain MSG/MAG under the same bias conditions. This allows the extraction of a maximum available gain cutoff frequency of 12 GHz (Fig. 4). The maximum stable gain versus frequency slope is in the range of 10 dB/dec, which is in good agreement with an MSG slope of usual FET devices. However, some discrepancies are noted between the ideal slope of 20 dB/dec for H_{21} and the measured one. This is again attributed to the difficulty in measuring low output conductance.

V. Conclusion

GaN/AlN/AlGaN/GaN nanowire MISFETs have been, for the first time, to our knowledge, fabricated and characterized for microwave applications. These transistors exhibit an intrinsic current-gain cutoff frequency of 5 GHz and a maximum available gain of 12 GHz. Moreover, the transconductance flatness means a very high linear behavior, which is very promising for future microwave applications such as low-noise amplifiers, high-linearity microwave sensors, and numerical systems. Future work will be focused on nanowire alignment, since NWs were randomly transferred onto the substrate, and only few of them were connected between ohmic contacts. Thus, we will be able to increase the NWs number connected between the ohmic contacts and so increase the saturation drain–current and decrease the input and output impedances.

Acknowledgment

The authors would like to thank Z. Bougrioua for her support to this cooperative work.

References

[1] Y. Okamoto, T. Nakayama, Y. Ando, A. Wakejima, K. Matsunaga, K. Ota, and H. Miyamoto, "230 W C-band GaN-FET power amplifier," *Electron. Lett.*, vol. 43, no. 17, pp. 927–929, Aug. 2007.

[2] A. M. Darwish, K. Boutros, B. Luo, B. D. Huebschman, E. Viveiros, and H. A. Hung, "AlGaN/GaN Ka-band 5-W MMIC amplifier," *IEEE Trans. Microw. Theory Tech.*, vol. 54, no. 12, pp. 4456–4463, Dec. 2006.

[3] U. K. Mishra, L. Shen, T. E. Kazior, and Y.-F. Wu, "GaN-based RF power devices and amplifiers," *Proc. IEEE*, vol. 96, no. 2, pp. 287–305, Feb. 2008.

[4] C. Y. Chang, G.-C. Chi, W.-M. Wang, L.-C. Chen, K.-H. Chen, F. Ren, and S. J. Pearton, "Electrical transport properties of single GaN and InN nanowires," *J. Electron. Mater.*, vol. 35, no. 4, pp. 738–743, Apr. 2006.

[5] Z. Zhong, F. Qian, D. Wang, and C. M. Lieber, "Synthesis of p-type gallium nitride nanowires for electronic and photonic nanodevices," *Nano Lett.*, vol. 3, no. 3, pp. 343–346, Mar. 2003.

[6] Y. Li, J. Xiang, F. Qian, S. Gradecak, Y. Wu, H. Yan, D. A. Blom, and C. M. Lieber, "Dopant-free GaN/AlN/AlGaN radial nanowire heterostructures as high electron mobility transistors," *Nano Lett.*, vol. 6, no. 7, pp. 1468–1473, Jul. 2006.

[7] O. Ambacher, B. Foutz, J. Smart, J. R. Shealy, N. G. Weimann, K. Chu, M. Murphy, A. J. Sierakowski, W. J. Schaff, L. F. Eastman, R. Dimitrov, A. Mitchell, and M. Stutzmann, "Two dimensional electron gases induced by spontaneous and piezoelectric polarization in undoped and doped AlGaN/GaN heterostructures," *J. Appl. Phys.*, vol. 87, no. 1, pp. 334–344, Jan. 2000.

[8] J. M. Bethoux, H. Happy, A. Siligaris, G. Dambrine, J. Borghetti, V. Derycke, and J. P. Bourgoin, "Active properties of carbon nanotube field-effect transistors deduced from S parameters measurements," *IEEE Trans. Nanotechnol.*, vol. 5, no. 4, pp. 335–342, Apr. 2006.