International Journal of High Speed Electronics and Systems
Vol. 19, No. 1 (2009) 7–14

World Scientific
www.worldscientific.com

5-TERMINAL THz GaN BASED TRANSISTOR WITH FIELD- AND SPACE-CHARGE CONTROL ELECTRODES

GRIGORY SIMIN[1], MICHAEL S. SHUR[2], REMIS GASKA[3]

[1]*Department of Electrical Engineering, University of South Carolina, 301 S. Main street., Columbia, SC, 29208, USA;*
[2]*Center for Integrated Electronics, Rensselaer Polytechnic Instutite, 110 8th Street Troy, New York 12180, USA, shurm@rpi.edu*
[3]*Sensor Electronic Technology Inc., 1195 Atlas Road, Columbia, SC 29209, USA*

We present a novel approach to achieve terahertz-range cutoff frequencies and maximum frequencies of operation of GaN based heterostructure field-effect transistors (HFETs) at relatively high drain voltages. Strong short-channel effects limit the frequency of operation and output power in conventional geometry GaN HFETs. In this work, we propose a novel device with two additional independently biased electrodes controlling the electric field and space-charge close to the gate edges. As a result, the effective gate length extension due to short channel effects is diminished and electron velocity in the device channel is increased. Our simulations show that the proposed five-terminal HFET allows achieving f_T=1.28 THz and f_{max}= 0.815 THz at the drain voltages as high as 12 V. Hence, this device opens up a new approach to designing THz transistor sources.

Keywords: HFETs; THz sources; Gallium Nitride; field-control electrodes

1. Introduction

Electronic devices operating in the THz frequency range will enable applications in radio astronomy, Earth remote sensing, radars and vehicle radars, scientific investigations, non-destructive testing of materials and electronic devices, chemical analysis, explosive detection, moisture content, coating thickness control, imaging, and wireless covert communications. In spite of great demand for efficient THz sources, compact and efficient transistor THz sources are not yet available. Achieving electronic device operation in the THz range is a complex multifaceted problem involving the control of electron velocity, electric field and potential profiles, access resistances, parasitic parameters, and electromagnetic coupling. Figure 1 clearly shows that electronic sources run out of steam above 0.1 THz, whereas photonic THz sources are more effective at frequencies above 10 THz. In the THz range, current electronic sources, such as photomixers and frequency multipliers can only deliver the RF powers in micro-watt range. THz lasers can emit high powers, up to 1 W, however, these devices are bulky, require high pumping powers and cannot be fabricated using integrated technology, which is a key feature of the modern functional system and building block design concept.

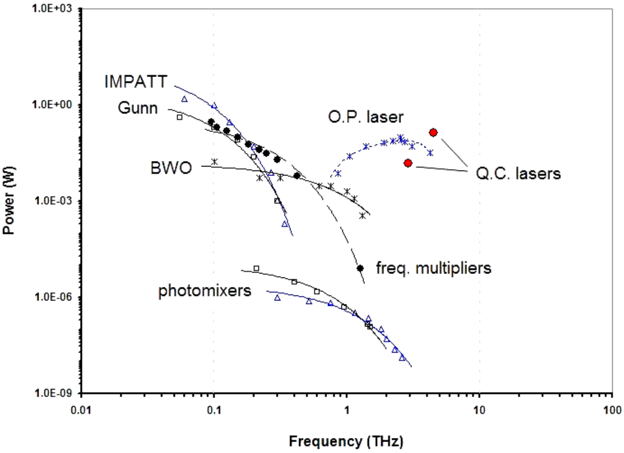


Figure 1. Illustration of THz gap problem (from [1] IEEE©2007). Filled circles correspond to cryogenic sources

One of the most important criteria for an efficient THz emission is the peak electron velocity.

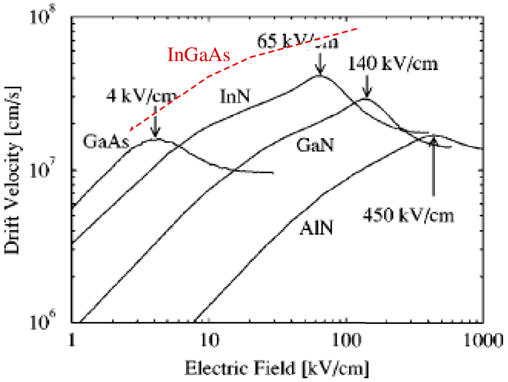


Figure 2. Drift electron velocity in various III-V materials (after [2, 3])

Figure 2 compares electron velocity- field dependencies in various III-V materials. InN (4.5 $\times 10^7$ cm/s) and InGaAs (close to 10^8 cm/s) have the highest peak velocities. GaN is the next to these materials with the peak velocity of 3×10^7 cm/s. In very short-gate devices, the average velocities under the gate might be considerably higher than the steady state values, due to so-called overshoot effects. [2]. Both InN and GaN have peak overshoot velocities are expected to be close to 10^8 cm/s. However, in InN material, the electron reach peak velocities at lower electric fields thus allowing for highest average velocities at longer gate length, around 0.15 µm as compared to 0.05 µm gate length required for GaN based devices.

Recently the cutoff frequencies in THz or sub-THz range have been demonstrated by a number of groups. The f_{max} above 1 THz has been achieved with InGaAs/InP HEMT [4], 300 GHz InP HEMT MMIC with 100 µW output power has been demonstrated by HRL. [5] Outstanding results have been achieved using advances in Si-technology. NMOS and PMOS devices fabricated using 45nm gate process with f_T of 485 GHz and 345 GHz respectively have been demonstrated by IBM. [6] The achievements in THz sources development correspond to the cutting edge III-V and Si technology; yet no THz operation and high-powers have been achieved simultaneously. The key obstacles to solving the problems remain relatively low current density in Si, GaAs and InP based devices, rapid degradation of cut-off frequencies with increasing drain bias (due to short-channel effects), and low operating voltages in devices with submicron inter-electrode spacing.

2. GaN Heterostructure Field-Effect Transistors

GaN based Heterostructure field-effect transistors (HFETs, a.k.a. HEMTs) exhibit record high electron densities and high peak electron velocity and mobilities in the 2D channel, which promise simultaneous achievement of cut-off frequencies, f_T, in the THz range and high output powers using nanoscale (~ 30 nm) gate technology. This makes GaN HFETs excellent candidates for high-power solid-state THz sources. The key problems precluding THz operation of GaN HFETs are related to effective gate length increase at high drain bias and access resistances causing significant degradation in f_T and f_{max} frequencies.

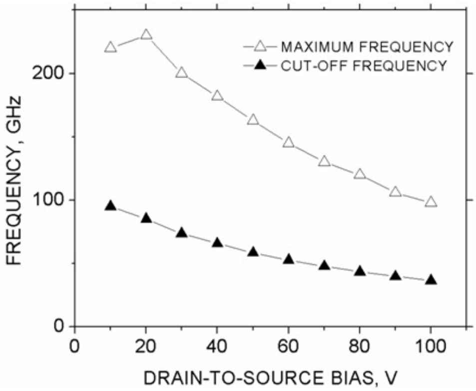


Figure 3. Cut-off frequencies of GaN based HFET vs. drain bias (from [7])

Figure 3 shows the dependence of f_T and f_{max} for GaN HFET with 150 nm long gate reported in [7]. The simulation results of [7] lead to important observation illustrating the difficulties in achieving THz operation with GaN HFETs. The effective gate length significantly exceeds the physical gate length. The difference is due to the 2DEG space charge region expansion into the gate-to-drain spacing with increasing drain bias. For the device with the actual gate length of 0.15 µm, the effective gate length reaches 0.25 µm at

14 V drain bias and around 0.5 μm at 32 V drain bias. It has been suggested that an additional field-controlling electrode (FCE) located in the near vicinity of the drain-side gate edge can efficiently control the extend of the space charge and thus the cut-off frequencies at high drain bias. Figure 4 shows the experimental data on the f_T – drain bias dependence for GaN HFETs with the drain FCE.

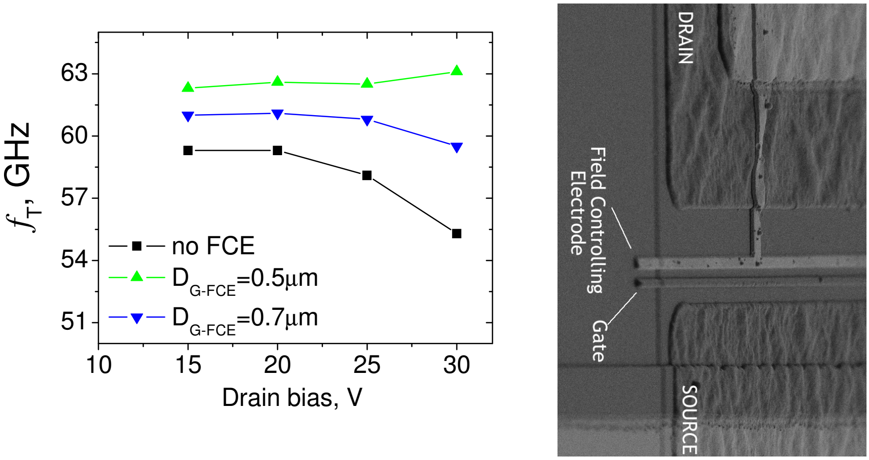


Figure 4. The F_T – drain bias dependencies for GaN HFET with 0.3 μm long gate and different gate-to FCE spacing (after [8])

As seen the addition of the FCE on the drain side of the gate allows for a complete suppression of the effective gate length increase and correspondingly leads to the nearly bias independent f_T. Another important set of limitations on the microwave performance of GaN HFETs arises from the access resistances. It is well known that, in GaN technology the achievable contact resistance values are significantly (around an order of magnitude) higher than those in GaAs technology. Contact annealing in GaN devices also requires much higher temperatures, leading to rough contact edges and calling for larger gate – to ohmic spacing to avoid premature breakdown and inter-electrode shortening. The source access resistance R_S comprising contact resistance R_C and source-gate opening resistance R_{SG} significantly reduces the external transconductance of sub-μm gate devices and leads to lower drain saturation currents. In addition, the total source and drain access resistances increase the knee voltage, thus requiring higher drain voltage to operate the device and to achieve high RF powers. Another problem associated with the access region is the 2DEG depletion due to the surface potential modulation. As a result, the carrier concentration in channel outside the gate becomes lower than that under the gate at high positive input signals. This leads to lower power gain and to an increase in the effective gate length at large input signals.

A new approach to significantly decreasing the contact resistance and allowing for a very tight source-gate-drain spacing was proposed in [9, 10]. This approach uses capacitively-coupled contacts (C^3) to fabricate microwave HFETs with low contact resistance at microwave frequencies and with independent control of induced carrier concentration in the source-gate and gate drain openings. [9]

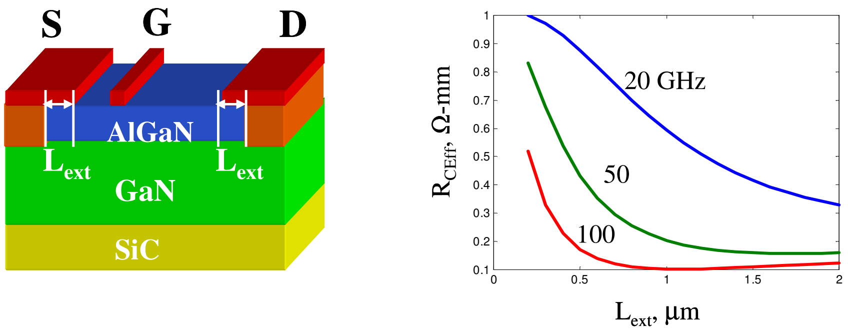
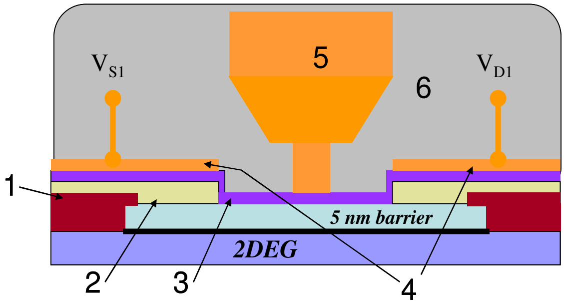


Figure 5. Schematic structure and effective contact resistance of the RF-enhanced contact to GaN HFET [9]

3. Proposed novel five-terminal GaN based THz HFET

In this work, we propose a novel device with two additional independently biased electrodes controlling the electric field and space-charge in the close vicinity of the gate edges, both at the source and drain sides . Source and drain field- and space-charge field controlling electrodes (FCEs) capacitively coupled with the source and drain ungated regions fundamentally change the HFET performance at THz frequencies. Additional bias voltages applied to the source and FCEs increase the electron concentration and velocity at the source edge of the gated channel and control the space-charge spread at the drain edge. As a result, the electron velocity under the gate electrode is increased and the space-charge penetration into the gate-drain region is minimized.

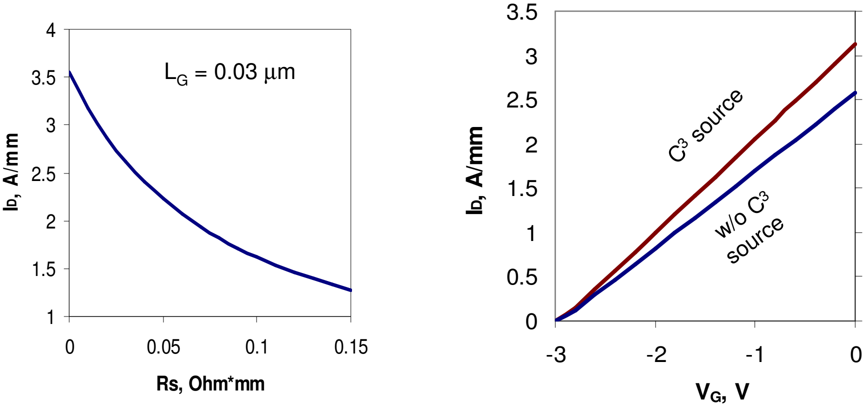


1 – Ohmic contact (low-T annealed);
2 – FCE isolation;
3 – Gate dielectric (HFO2)
4 – Source and Drain FCEs/ RF-enhanced contacts;
5 – 10 nm Gate
6 – Flash-over suppressing encapsulation

Figure 6. Schematic structure of 5-terminal THZ HFET with field-controlling electrodes (FCEs)

Due to very short gate lengths in THz HFETs, even small values of the source access resistance have significant effect on the device peak current and therefore, on the transconductance and cut-off frequency. The effect of source resistance on the

MOSHFET with the gate length L_G = 0.03 µm is illustrated in Fig. 7 (a). The threshold voltage V_T= -3 V was used in these simulations.



(a) (b)

Figure 7. (a): Effect of the source access resistance on the MOSHFET peak drain current; (b): Transfer characteristics of the MOSHFET with and without source C^3 electrode.

The effect of source – drain access resistance reduction due to capacitively-coupled source electrode is illustrated in transfer characteristics of Fig. 7 (b). The transfer characteristics were simulated using the MOSHFET with the gate length L_G = 0.03 µm and the source-gate spacing of 0.1 µm. The AlGaN barrier thickness was 10 nm. For the device without C^3 source electrode, the access resistance of the source-gate spacing was calculated using the sheet resistance R_{SH} = 300 Ω/sq. For the device with C^3 source electrode under positive bias inducing additional electrons into the 2 D channel, we used the data of [11] providing the maximum additional carrier concentration that can be induced in the AlGaN/GaN 2DEG channel. According to [11], the induced carriers can reduce R_{SH} by a factor of two. The value of R=150 Ω/sq was used to simulate the transfer curve for the MOSHFET with source C^3 electrode in Fig. 7 (b).

The ADS simulations for the proposed 5-terminal GAN HFET at 10 V drain bias are shown by solid lines in Figure 8. For the ADS simulations we used a MOSFET level 3 model to simulate the intrinsic HFET. The model input data were recalculated using parameters specific for the GaN HFET, such as 2DEG equilibrium sheet density, threshold voltage, barrier and dielectric thickness etc. The access regions were simulated using equivalent circuit of the RF-enhanced contacts extracted from MATLAB simulations (the data presented in Figure 5). Physical gate length was taken as 0.01 µm. The effective gate length for the device without FCE, was taken as drain bias dependent, increasing from the geometrical value at zero drain bias to 80 nm at 10 V drain bias according to the data from reference [7]. For the 5-terminal device with FCEs, the 0.02 µm gate FCE separation was assumed. Correspondingly, the effective gate length was kept at 30 nm independently of the drain bias as the gate depletion region extension is controlled by the gate – FCE spacing. The effective electron velocity was estimated using the technique and results of [7]. For a conventional geometry HFET, the electron velocity was $v_m = 1.5\times10^7$ *cm/s* whereas for the HFET with FCEs, $v_m = 2.7\times10^7$ *cm/*s (see Fig. 1.).

As seen from the simulation results of Figure 8, the novel approach allows achieving f_T=1.28 THz and f_{max}= 0.815 THz at the drain voltages as high as 10 V. The proposed device, therefore, opens up a new approach to fabricating high-power THz transistor sources.

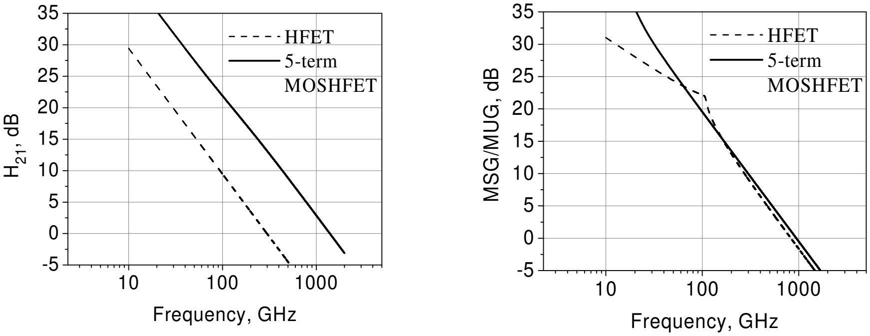


Figure 8. Current and power gain of 5-terminal HFET simulated with ADS.

Table 1 shows the summary of the input device parameters and performance of the proposed 5-terminal HFETs in comparison with the conventional geometry HFET.

Table 1

Parameter	5-Term. HFET	Regular HFET
Layout	L_G = 10 nm; W = 15 um;	
Effective gate length	L_G = 30 nm	L_G = 80 nm
Electron velocity	2.7 10^7 cm/s	1.5 10^7 cm/s
f_T	1.28 THz	300 GHz
f_{MAX}	815 GHz	700 GHz

Expected output powers of the proposed device can be estimated as follows. Consider the 5-terminal MOSHFET with the total width of 20 μm. The drain bias of 5 V can be applied across this device assuming that the surface flash-over breakdown effects are suppressed by the dielectric encapsulation. In this case, the highest electric field existing across the gate – FCE region, is 5V/0.02 μm is 2.5 MV/cm, not exceeding the breakdown filed for GaN. The peak drain current of such device, according to the data of Reference [11], is $I_M \approx 3.5$ A/mm × 20×10^{-3} mm = 70 mA. The output power at the drain bias V_D = 5 V and the knee voltage $V_{KN} = 2$ V is $P_m \approx I_M \times (V_D - V_{KN})/4 \approx 35$ mW. This power is much higher than that ever obtained using InGaAs-based or other THz transistors.

In conclusion, we considered the possibility of using high electron velocities in III-N materials to penetrate the THz range with higher power than InGaAs based devices. We analyzed the factors preventing the III-N devices from achieving THz cut-off frequencies. These include effective gate length extension and high access resistances. We proposed a novel 5-terminal device with field-controlling electrodes which has a promise to achieving the current cutoff frequency of 1.28 THz and f_{max} of 815 GHz at the drain bias as high as 10 V.

4. Acknowledgement

The work at RPI has been supported by the National Science Foundation under the auspices of I/UCRC "Connection One." The work at SET Inc. and USC was supported by the SBIR Phase I contract monitored by A. L. de Escobar, E. Wong and W. Kordela. The work at USC was supported by the National Science Foundation under Grant No. 0621931 monitored by Dr. P. Fulay.

References

[1] W.J. Stillman and M.S. Shur, Closing the Gap: Plasma Wave Electronic Terahertz Detectors, Journal of Nanoelectronics and Optoelectronics, Vol. 2, Number 3, pp. 209-221, December 2007
[2] B. E. Foutz, S. K. O'Leary, M. S. Shur, and L. F. Eastman, J. Appl. Phys. 85, 7727 (1999)
[3] v(E) for InAs (from Hess and Brennan (1984), See M.P. Mikhailova Handbook Series on Semiconductor Parameters, vol.1, M. Levinshtein, S. Rumyantsev and M. Shur, ed., World Scientific, London, 1996, pp. 147-168.
[4] R. Lai, X. B. Mei, W.R. Deal, W. Yoshida, Y. M. Kim, P.H. Liu, J. Lee, J. Uyeda, V. Radisic, M. Lange, T. Gaier, L. Samoska, A. Fung, Sub 50 nm InP HEMT Device with Fmax Greater than 1 THz, IEDM Technical Digest, p. 609 (2007)
[5] http://www.hrl.com/html/techs_mel.html
[6] Sungjae Lee, Basanth Jagannathan, Shreesh Narasimha, Anthony Chou, Noah Zamdmer, Jim Johnson, Richard Williams, Lawrence Wagner, Jonghae Kim, Jean-Olivier Plouchart, John Pekarik, Scott Springer and Greg Freeman, Record RF performance of 45-nm SOI CMOS Technology, IEDM Technical Digest, p. 225 (2007)
[7] V. O. Turin, M. S. Shur, and D. B. Veksler, Simulations of field-plated and recessed gate gallium nitride-based heterojunction field-effect transistors, International Journal of High Speed Electronics and Systems, vol. 17, No. 1 pp. 19-23 (2007)
[8] Pala, N. Yang J., Z. Koudymov, A. Hu, X. Deng, J. Gaska, R. Simin, G. Shur, M. S. Drain-to-Gate Field Engineering for Improved Frequency Response of GaN-based HEMTs, Device Research Conference, 2007 65th Annual, 18-20 June 2007, pp. 43-44
[9] G. Simin, Wide Bandgap Devices with Non-Ohmic Contacts, 210th Electrochemical Society Meeting 2006, Cancun, Mexico October 29-November 3, 2006
[10] G. Simin, Z-J. Yang, M. Shur, High-power III-Nitride Integrated Microwave Switch with capacitively-coupled contacts, Microwave Symposium, IEEE/MTT-S International, pp. 457-460 (2007)
[11] A. Koudymov, H. Fatima, G. Simin, J. Yang, M. Asif Khan, A. Tarakji, X. Hu, M. S. Shur, and R. Gaska Maximum Current in Nitride-Based Heterostructure Field Effect Transistors Appl. Phys. Lett, V. 80 pp. 3216-3218 (2002)