Extended Abstracts of the 1999 International Conference on Solid State Devices and Materials, Tokyo, 1999, pp. 210-211

C-5-3

$Al_xGa_{1-x}N$/GaN Material Properties and HEMT Shunt Switch RF Performance

Nikolai Drozdovski and Robert Caverly

Electrical and Computer Engineering Department, Villanova University,
800 Lancaster Ave., Villanova, PA 19085, USA
Phone: +1-610-519-5660 Fax: +1-610-519-4436 e-mail: drozd@ece.vill.edu

1. Introduction

Multifunction RF and microwave systems require a high degree of control in a high power, multisignal environment. The control elements traditionally used in these applications are silicon or GaAs PIN diodes and GaAs MESFETs [1,2]. Compared with PIN diode devices, FET-based control devices can provide lower insertion loss, higher switching speed performance with minimal DC bias power (and a minimal bias network) needed for the switching action [3]. The main disadvantage of current FET-based microwave and RF switches are their relatively low breakdown voltage (about 10 volts) and, therefore, their low power-handling capability.

Recent advances in semiconductor technologies based on wide bandgap materials such as GaN promise to extend the power level of FET-based microwave circuits by at least a factor of five due to their higher breakdown voltages [4-5], extending the useful power range of GaN FET-based control components to the tens of watts. The study of one of these structures, the HEMT, for microwave and RF power control purposes is especially important because of their use in small size, high-density front end applications or in multifunction systems. In this paper we discuss GaN material properties that influence switch insertion loss and isolation, the main design parameters for microwave control circuits.

2. HFET small-signal characteristics

For control applications, the HFET is used as two-terminal (source-drain) microwave device. The third terminal (gate), connected to external DC control voltage supply, is isolated from the microwave circuit. The DC voltage is used to switch transistor from the on-state to the off-states and vice versa. A small-signal equivalent circuit for the GaN-based HEMT (Fig.1) consists of parallel resistanse R_{sd} and capacitance C_{sd}. These values are determined by semiconductor material properties, transistor geometry and DC gate control voltage [6].

From the equivalent circuit, R_{sd} can be written as:

$$R_{sd} = R_{ch} + R_s + R_d, \tag{1}$$

where, R_{ch} is the heterointerface (or channel) resistance, and R_s and R_d are the source and drain resistance, respectively.

The contribution of R_s and R_d to the total on-state resistance R_{sd} is neglectable compared with the channel reistance R_{ch}. Since the two dimensional electron gas (2DEG) governs the resistance in the conductive channel, the total channel resistance may be estimated as:

$$R_{ch} = \rho_S \times \frac{L_{ch}}{W}, \tag{2}$$

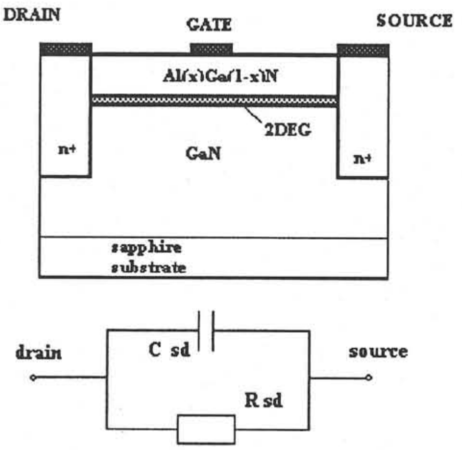

Figure 1. HEMT and its small-signal equivalent circuit.

where, ρ_S is the sheet resistance of $Al_xGa_{1-x}N$/GaN interface, W is the gate width of HFET, and L_{ch} is the channel length (drain-source distance). The value of the sheet resistance is computed as:

$$\rho_s = \frac{1}{\mu_n n_s q}, \tag{3}$$

where q is the single charge, μ_n is the low-field mobility of 2DEG and n_s is the two-dimensional electron gas (2DEG) density. which is the function of the DC control gate voltage and interface geometry [7].

The capacitance model includes both voltage dependent and parasitic capacitances. The important parasitics are the source and drain metal coupling capacitance through air to the gate, the extrinsic capacitances that couple the source and drain above the semiconductor, and the intrinsic capacitances that couple through the GaN and substrate layers. The last three capacitances are present only in the off-state, when the 2DEG is suppressed by the gate voltage. These capacitances may be estimated using standard equations for MESFETs [8]. The voltage dependent capacitances are presented by source-gate and drain-gate capacitances [7] and capacitances between gate and inner side of the drain or source contacts.

Figure 2 shows typical computed and experimental DC control gate voltage characteristics of source-drain resistance at frequency of 2.5 GHz. In the off-state R_{sd} (or R_{off}) is on the order of kiloohms while in on-state R_{sd} (or R_{on}) is about 30 Ohms. Source-drain capacitance C_{sd} does not exceed several tens of femtofarades in both states.

The device used for the experimental observations had a gate width of 150 μm, a gate length of 0.3 μm, and source-drain distance of 2 μm.

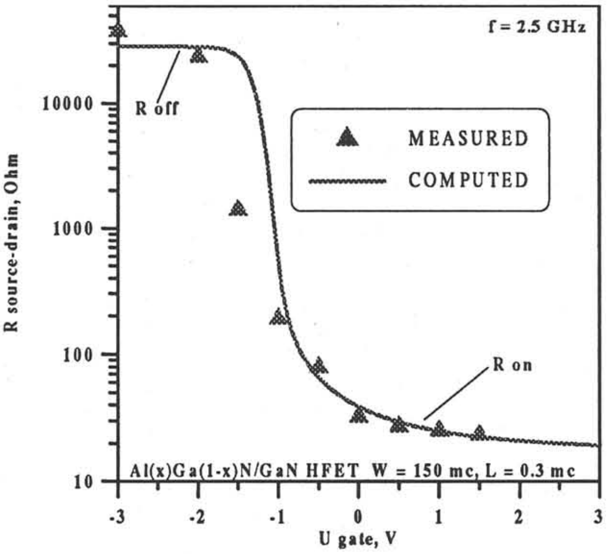

Figure 2. Resistance R_{sd} against DC gate control voltage.

3. Switch small-signal characteristics

The main control HEMT parameters are on-state resistanse R_{on} (DC gate voltage is above the threshold voltage) and off-state capacitance C_{off} (DC voltage is beyond the threshold voltage). They determine the RF impedances in these states and therfore two main RF switch parameters such as insertion loss and isolation are dependent on them. In case of the shunt HEMT configuration (frame, Fig.3) isolation is determined by R_{on}, while insertion loss by C_{off}.

For the HEMTs the value of the sheet resistance of the $Al_xGa_{1-x}N/GaN$ interface is very important. It strongly influences the on-state resistance, therefore strongly affecting the isolation. Figure 3 illustrates this influence. It reflects computed GaN HFET shunt switch losses versus DC gate voltage for different values of sheet resistance.. There is no influence of the sheet resistance on the level of insertion loss, because they are determined by the C_{off}, but there is significant change in isolation as sheet resistance is changed.

The measured resistance of the test GaN HEMT (see Fig.2) is relatively high (about 30 Ohms) because of the relatively high sheet resistance of about 1900 Ω/□ in the devices. The measured isolation in this case did not exceed several decibels. However, it is in a good agreement with the computed results. The use of lower sheet resistance of $Al_xGa_{1-x}N/GaN$ heterointerface will yield lower resistance R_{on} and higher isolation. A surface resistivity of 500 Ω/□, for example, will lower the resistance R_{on} about three times and will result in higher isolation. It should be to noted that the insertion loss will remain the same over the change in resistivity.

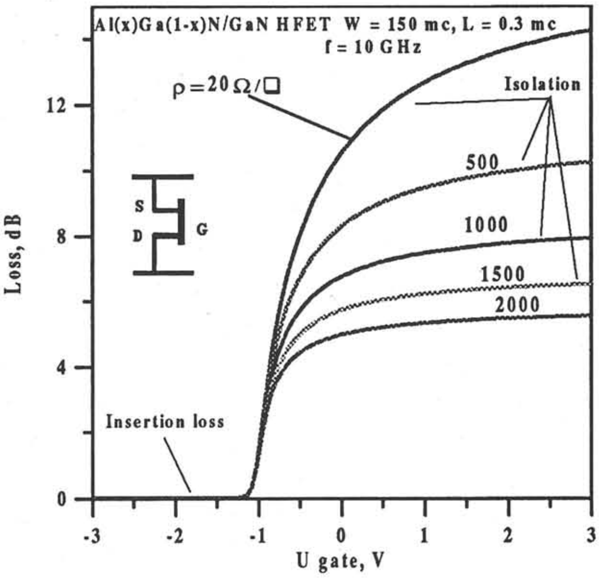

Figure 3. Shunt HEMT configuration vs. DC gate control voltage.

4. Conclusion

$Al_xGa_{1-x}N/GaN$ HEMTs in a shunt switch configuration were under studied. The heterointerface sheet resistance strongly influences the RF switch characteristics using these devices, primarily the shunt isolation. It is anticipated that series insertion loss will improve by reducing the sheet resistance.

Acknowledgments

This work was supported by the Office of Naval Research (Dr. J. Zolper) under contact number N000149810895. The GaN devices tested were generously supplied by L. Eastman and B. Green of the Department of Electrical and Computer Engineering of Cornell University.

References

[1] J.F.White, Microwave Semiconductor Engineering, 1982

[2] Y.Ayalsi, Microwave Switching with GaAs FETs, Microwave J., **25**, 719 (1982)

[3] A.Gopinath, Comparison of GaAs MESFET and GaAs p-i-n Diodes as Switch Elements, IEEE Electr. Device Lett., **6**, 505 (1985)

[4] U.Mishra, Y-F.Wu, B.Keller, S.Keller, S.Denbaars, GaN Microwave Electronics, IEEE Trans. on MTT, **46**, 756 (1998)

[5] M.S.Shur, GaN Based Transistor for High Power Appli-cations, Solid-State Electronics, **42**, .2131, (1998)

[6] N.Drozdovski, R.Caverly, GaN Based High Electron Mobility Transistors for Microwave and RF Control Applications, will be presented at EuMC'99, (1999)

[7] S.Sze, Modern Semiconductor Device Physics, (1998) p.109

[8] N.Jain, R.Gutmann, Modeling and Design of GaAs MESFET Control Devices for Broad-Band Applications", IEEE Trans. on MTT, **38**, 109, (1990)