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ScienceDirect

The Journal of China Universities of Posts and Telecommunications

October 2016, 23(5): 56–60
www.sciencedirect.com/science/journal/10058885

http://jcupt.bupt.edu.cn

Small-signal switch model of GaN HEMTs for MMIC applications

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Abstract

Gallium nitride (GaN) high electron mobility transistor (HEMT) with symmetrical structure as a control device is discussed in this paper. The equivalent circuit model is proposed on the basis of physical and electrical properties of the GaN HEMT device. A transistor with 0.5 μm gate length and 6 × 125 μm gate width is fabricated to verify the model, which can be treated as a single pole single throw (SPST) switch due to the ON state and OFF state. The measurement results show a good agreement with the simulation results, which demonstrates the effectiveness of the proposed model.

Keywords GaN HEMT, switch model, symmetrical structure, MMIC

1 Introduction

Currently, p-i-n diodes and gauium arsenide (GaAs) metal-semiconductor field effect transistor (MESFETs) are widely utilized as microwave and radio frequency (RF) semiconductor control components [1–2]. Plenty of direct current (DC) power is commonly used up in p-i-n diode, which is not suitable for low loss applications. GaAs field effect transistors (FETs) can provide low insertion loss and high switching speed without DC bias power consuming in theory [3–4]. However, the relatively low breakdown voltage (<10 V) limits the applications of GaAs FETs in various power electronics [5]. When the device operates in the high impedance state, the entire RF voltage is dropped across the drain–source terminals of the transistor. Any voltage higher than the breakdown voltage may introduce unexpected conduction, decrease of the isolation or destruction of the device [5–6]. Considering the low breakdown voltage, the output power of GaAs FETs is limited to a few watts.

As a promising wide band-gap device, the disruptive field intensity of GaN FFTs may even be higher than 5 MV/cm, which is far greater than that of GaAs FETs [7]. Therefore, GaN transistors have an extraordinary foreground to be applied as high power and low loss control devices [8–9]. Most models in GaN technique have been developed for power amplifier applications where the FETs work in the saturation (constant current) region [10]. Asymmetrical structure is utilized to obtain power gain. To this end, the distance of gate-drain is much larger than that of gate-source to endure the high breakdown voltage of the high power devices. However, these models are not appropriate for control devices operating in the cutoff or triode region.

The bilateral control switching devices are widely used in single-way or multi-way transmitter-receiver modules in time-division system, which requires the symmetrical source terminal and drain terminal. Fig. 1 depicts symmetrical structure of GaN for switching devices. The T-type gate is located in the central of source and drain, which is different from the asymmetrical structure [9]. As shown in Fig. 1, the FET with symmetrical property allows for the interchange of drain and source, which is quite important for monolithic microwave integrated circuit (MMIC) modules (i.e., attenuator or phase shifter). Accurate simulations for switching circuit designs depend on accurate component models [11]. However, to the best knowledge of us, there has been few works focused on this issue so far. Therefore, it is necessary to take GaN

Received date: 05-07-2016
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DOI: 10.1016/S1005-8885(16)60058-4

component models into account during the research of GaN switch circuits.

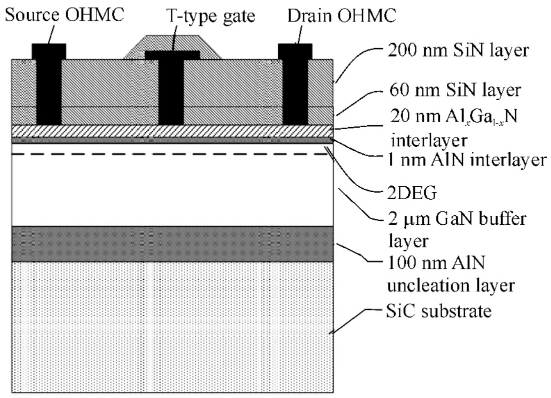

Fig. 1 GaN HEMT with symmetrical structure

2 Equivalent model of GaN HEMT switching devices

Switching transistor is a three-port device, of which the source and drain are the RF signal input and output ports, respectively. The gate terminal is connected to a DC voltage source, which controls the HEMT operating mode. The charge density in the two-dimensional electron gas (2DEG) is under control of the gate voltage. And the conductive channel comes into being simultaneously. The on-state resistance R_{on}, which determinates the insertion loss of microwave signal through the device, is governed by the total source–drain resistance. Biased below the threshold voltage, the 2DEG in the channel is completely depleted. Meanwhile, the conductive channel disappears, corresponding to the high-impedance state. However, it is not the resistance but capacitance C_{off} that plays a crucial role in off-state. The capacitance can deprave the isolation performance of the switch, i.e., the signal can leak through the capacitances [12–14]. The cross-sectional equivalent-circuit of GaN HEMT symmetrical structure is shown in Fig. 2.

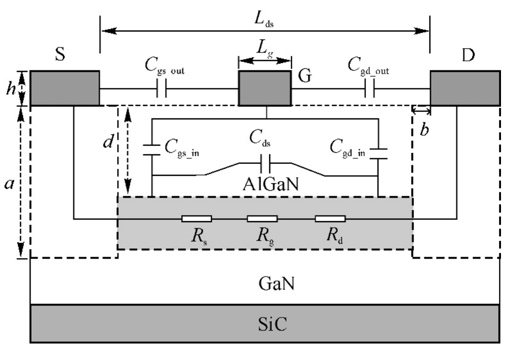

Fig. 2 Equivalent-circuit of GaN HEMT with symmetrical structure

The on-state resistances comprise the parasitic resistances and the channel resistance. And the latter is composed of several resistance components and can be written as:

$$R_{\mathrm{ds}} = R_{\mathrm{g}} + R_{\mathrm{s}} + R_{\mathrm{d}} \tag{1}$$

where R_{g}, R_{s} and R_{d} are the channel resistance, the source-gate and drain-gate channel resistances respectively and they can be calculated by:

$$R_{\mathrm{g}} = \frac{L_{\mathrm{g}}}{W} R_{\mathrm{sh}}$$

$$R_{\mathrm{s}} = R_{\mathrm{d}} = \frac{L_{\mathrm{sd}} - L_{\mathrm{g}}}{2W} \frac{1}{q\mu_0\mu_{\mathrm{r}}n_0}$$

$$n_0 = \frac{\varepsilon_i \eta V_{\mathrm{th}}}{2q(d+\Delta d)}$$

where L_{g} is the length of the gate, W is the gate width and R_{sh} is the channel resistance of the unit area. L_{sd} is the distance between the source or drain poles, μ_0 and μ_{r} are the permeability of free space and the relative permeability, and n_0 is the intrinsic concentration of the 2DEG in the channel. ε_{i} is the dielectric constant of the $\mathrm{Al}_x\mathrm{Ga}_{1\text{-}x}\mathrm{N}$ layer, d is the thickness of the $\mathrm{Al}_x\mathrm{Ga}_{1\text{-}x}\mathrm{N}$ layer, and Δd is the correction factor, of which the thickness is a few nanometers.

C_{gs} can be divided into the parasitic capacitance and internal diode capacitance. The parasitic capacitances come from the edges of T-type gate. When the device physical dimension is fixed on, the height of the electrode is confirmed, and the capacitance is mainly determined by the distance of the gate-source and gate-drain. For symmetrical source and drain the parasitic capacitances are given by:

$$C_{\mathrm{gs\_out}} = C_{\mathrm{gd\_out}} = \frac{\varepsilon A}{t} = \frac{\varepsilon W h}{0.5\left(L_{\mathrm{ds}} - L_{\mathrm{g}}\right)} \tag{2}$$

where h is the thickness of the metal electrodes.

The internal capacitance is the capacitance of Schottky barrier diode, which can be defined by [15]:

$$C_{\mathrm{gs\_in}} = C_{\mathrm{gd\_in}} = \frac{C_{\mathrm{g0}}}{\left[1+\left(\frac{n_{\mathrm{s}}}{n_{\mathrm{max}}}\right)^{\gamma}\right]^{1+\frac{1}{\gamma}}} \tag{3}$$

$$C_{\mathrm{g0}} = \frac{C_{\mathrm{i}}}{1-2\mathrm{e}^{\left|-\frac{V_{\mathrm{g}}-V_{\mathrm{T}}}{\eta V_{\mathrm{th}}}\right|}} \tag{4}$$

$C_{\mathrm{i}} = WL\varepsilon(d+\Delta d)$ is the gate-channel capacitance when V_{g} is above the threshold. The total capacitances of C_{gs} and C_{gd} are given by: