Static performance model of GaN MESFET based on the interface state*

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Abstract: This paper presents a new model to study the static performances of a GaN metal epitaxial-semiconductor field effect transistor (MESFET) based on the metal–semiconductor interface state of the Schottky junction. The *I*–*V* performances of MESFET under different channel lengths and different operating systems (pinch-off or not) have been achieved by our model, which strictly depended on the electrical parameters, such as the drain-gate capacity C_{gd}, the source–gate capacity C_{gs}, the transconductance, and the conductance. To determine the accuracy of our model, root-mean-square (RMS) errors were calculated. In the experiment, the experimental data agree with our model. Also, the minimum value of the electrical parameter has been calculated to get the maximum cut-off frequency for the GaN MESFET.

Key words: GaN MESFET; static performance model; interface states

Supplementary Section 1

Potential and electric field calculation

Due to the difficulties imposed by the edge effects, several simplifying assumptions were modeled for the active region of the channel of MESFET. Assuming that the channel length was much greater than its thickness in the space charge region, the variation of the electric field in the structure direction was much larger than in the longitudinal direction. The Poisson equation reduces to:

$$\frac{\mathrm{d}^2 V(x,y)}{\mathrm{d}y^2} = -\frac{q}{\varepsilon} N_\mathrm{d}(x,y), \tag{1}$$

where $V(x, y)$ was the total electrostatic potential variation across the space charge region, $\varepsilon = \varepsilon_0\, \varepsilon_{\mathrm{GaN}}$, ε_0 was the vacuum permittivity, $\varepsilon_{\mathrm{GaN}}$ was the dielectric constant and N_d the donor density.

The two sides of the Eq. (1) were integrated between $h(x)$ and y, with the proviso $\frac{\mathrm{d}(x,y)}{\mathrm{d}y} = 0$ at $y = h$. We obtain:

$$\frac{\mathrm{d}V(x,y)}{\mathrm{d}y} = -\frac{1}{\varepsilon}\int_{h(x)}^{y} qN_\mathrm{d}(x,y)\,\mathrm{d}y = \frac{1}{\varepsilon}\left(\int_{0}^{h(x)} qN_\mathrm{d}(x,y)\,\mathrm{d}y - \int_{0}^{y} qN_\mathrm{d}(x,y)\,\mathrm{d}y\right) \tag{2}$$

where $h(x)$ was the thickness of the space charge region at a point x of the channel.

Otherwise, the expression of the channel voltage in the plane following x, $V(x, y)$ can be deduced:

$$V(x,y) = \frac{q}{\varepsilon}\int_{0}^{h(x)} yN_\mathrm{d}(x,y)\,\mathrm{d}y + V_\mathrm{g} - V_{\mathrm{bi}}. \tag{3}$$

V_{bi} was the Schottky barrier voltage and V_g the gate voltage.

For a uniform doping and a space charge region (SCR) empty from carriers, we have $N_\mathrm{d}(x, y) = N_\mathrm{d}$, and Eq. (3) becomes:

$$V(x) = \frac{qN_\mathrm{d}}{2\varepsilon} h^2(x) + V_\mathrm{g} - V_{\mathrm{bi}}. \tag{4}$$

Develop $\frac{\mathrm{d}V(x,y)}{\mathrm{d}x}$ under the form $\frac{\mathrm{d}V(x,y)}{\mathrm{d}h(x)} \times \frac{\mathrm{d}h(x)}{\mathrm{d}x}$,

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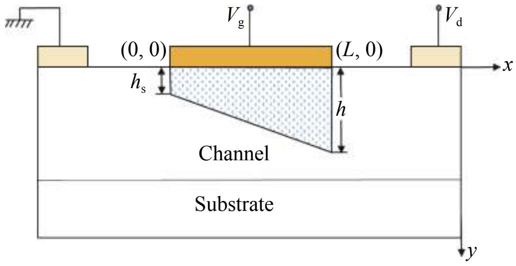

Fig. S1. (Color online) Active region of the MESFET

$$\frac{\mathrm{d}V(x,y)}{\mathrm{d}h(x)} = \frac{q}{\varepsilon} h(x) N_{\mathrm{d}}(h(x)). \tag{5}$$

The electric field in the SCR was deduced by $E = -\nabla(V)$:

$$E_y(x) = \frac{qN_{\mathrm{d}}}{\varepsilon}(y - h(x)), \tag{6}$$

$$E_x(x) = -\frac{qN_{\mathrm{d}}}{\varepsilon} h(x) \frac{\mathrm{d}h(x)}{\mathrm{d}x}. \tag{7}$$

In the following, hypothesize the gradual channel and use similar triangle properties to calculate the expression of the thickness of the space charge region at a point x of the channel $h(x)$ based on its values on source side h_s and drain side h_d

$$h(x) = \frac{h_{\mathrm{s}} - h_{\mathrm{d}}}{L} x + h_{\mathrm{s}}. \tag{8}$$

The calculations above neglect the contribution of SCR under the free surface in the potential.

Supplementary Section 2

Devices with interface states have the higher gate leakage. Therefore, controlling the thickness of the channel by the gate potential was weaker. Taking into account the interfacial states causes a non-ideality of the MESFET Schottky barrier. The interfacial states have consumed a finite quantity of V_{gs}. The potential amplitude which varies the channel height was different from the applied V_{gs}. In such circumstances, a simulation done by considering V_{gs} as a variable cannot predict the behavior of the device accurately.

$$V_{\mathrm{gs}}\,[\text{The gate}-\text{source region}] = V_{\mathrm{gs}}\,[\text{Interface region}] + V_{\mathrm{gs}}\,[\text{Depletion region}]. \tag{9}$$

As the above expression indicates, the applied voltage was consumed by the interfacial states. If the states density at a Schottky junction interface was high, the contribution of V_{gs} [Interface region] was too high to be ignored. What was observed experimentally would not agree to the theory of GaN MESFET. To solve this problem and set the exponential nature of the density of states, the following expression was given to change V_{gs}:

$$V_{\mathrm{eff}} = \frac{V_{\mathrm{gs}}}{1 + x\mathrm{e}^{V_{\mathrm{gs}}}}. \tag{10}$$

The parameter x was an adjustment variable that simulates the quality of the Schottky barrier. As $x = 0$, the Schottky barrier was supposed to be perfect and the interface states effects were negligible. Thus, modeling becomes more flexible, so each GaN device has a specific variable x, which gives us an idea about the quality of the metal–SC junction.

Knowing that:

$$h_{\mathrm{s}} = \left[\frac{2\varepsilon}{qN_{\mathrm{d}}}\left(V_{\mathrm{bi}} - \frac{V_{\mathrm{gs}}}{1 + x\mathrm{e}^{V_{\mathrm{gs}}}}\right)\right]^{1/2}, \tag{11}$$

$$h_{\mathrm{d}} = \left[\frac{2\varepsilon}{qN_{\mathrm{d}}}\left(V_{\mathrm{bi}} + V_{\mathrm{d}} - \frac{V_{\mathrm{gs}}}{1 + x\mathrm{e}^{V_{\mathrm{gs}}}}\right)\right]^{1/2}, \tag{12}$$

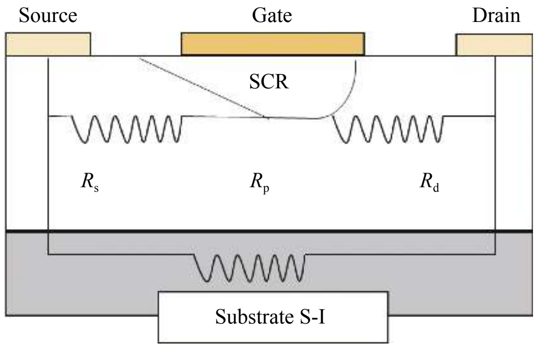

Fig. S2. (Color online) Parasitic resistances in the GaN MESFET.

$$h(x)=\left[\frac{2\varepsilon}{qN_{\mathrm{d}}}\left(V(x)+V_{\mathrm{bi}}-\frac{V_{\mathrm{gs}}}{1+x\mathrm{e}^{V_{\mathrm{gs}}}}\right)\right]^{1/2}, \tag{13}$$

the drain current expression becomes of the form:

$$I_{\mathrm{d}}=\frac{z\mu qN_{\mathrm{d}}a}{L}\left(V_{\mathrm{d}}-\frac{2}{3\sqrt{V_{\mathrm{p}}}}\left(V_{\mathrm{bi}}+V_{\mathrm{d}}-\frac{V_{\mathrm{gs}}}{1+x\mathrm{e}^{V_{\mathrm{gs}}}}\right)^{3/2}+\frac{2}{3\sqrt{V_{\mathrm{p}}}}\left(V_{\mathrm{bi}}-\frac{V_{\mathrm{gs}}}{1+x\mathrm{e}^{V_{\mathrm{gs}}}}\right)^{3/2}\right), \tag{14}$$

where Z is the channel width, a is its thickness and L its length.

This expression, that gives the drain current versus the two polarization voltages, will be rewritten differently according to the operation region (turn-on or the pinch-of region), which depends essentially on V_{d}.

First, the linear region, where the drain current varies linearly with the drain voltage V_{d}; in this case, the drain voltage respects the condition: $V_{\mathrm{d}} \ll V_{\mathrm{bi}}-V_{\mathrm{eff}}$.

Therefore, the expression of drain current is:

$$I_{\mathrm{d}}\left(V_{\mathrm{d}},V_{\mathrm{g}}\right)=I_{\mathrm{pL}}\left[\frac{V_{\mathrm{d}}}{V_{\mathrm{p}}}-\frac{2}{3}\left(\frac{V_{\mathrm{bi}}-\frac{V_{\mathrm{gs}}}{1+x\mathrm{e}^{V_{\mathrm{gs}}}}+V_{\mathrm{d}}}{V_{\mathrm{p}}}\right)^{3/2}+\frac{2}{3}\left(\frac{V_{\mathrm{bi}}-\frac{V_{\mathrm{gs}}}{1+x\mathrm{e}^{V_{\mathrm{gs}}}}}{V_{\mathrm{p}}}\right)^{3/2}\right] \text{ with : } I_{\mathrm{pL}}=\frac{(qN_{\mathrm{d}})^2 z\mu_0 a^3}{2\varepsilon L}. \tag{15}$$

Second, the saturation region, in which the current saturates at I_{dsat}.

$$V_{\mathrm{d}}=V_{\mathrm{dsat}}=V_{\mathrm{p}}-V_{\mathrm{bi}}+V_{\mathrm{gsT}}. \tag{16}$$

Therefore, the expression of drain current becomes:

$$I_{\mathrm{dsat}}=I_{\mathrm{ps}}\left[\frac{1}{3}-\left(\frac{V_{\mathrm{bi}}-\frac{V_{\mathrm{gs}}}{1+x\mathrm{e}^{V_{\mathrm{gs}}}}}{V_{\mathrm{p}}}\right)+\frac{2}{3}\left(\frac{V_{\mathrm{bi}}-\frac{V_{\mathrm{gs}}}{1+x\mathrm{e}^{V_{\mathrm{gs}}}}}{V_{\mathrm{p}}}\right)^{3/2}\right] \text{ with : } I_{\mathrm{ps}}=\frac{(qN_{\mathrm{d}})^2 za^3\mu_0}{2\varepsilon L\left(1+\left(\frac{E}{E_{\mathrm{c}}}\right)^n\right)^{1/n}}. \tag{17}$$

To obtain the extrinsic performances of the device (I_{ds}, V_{ds}, V_{gs}), we have to take into account the effect of the source and the drain access parasitic resistances R_{s} and R_{d} respectively. Also, the effect of the resistance R_{p} parallel to the channel, is due essentially to the dispersive effects of the substrate.

To get the real expressions of I_{ds} performances (V_{ds}, V_{eff}), just replace the intrinsic terms by extrinsic terms in all previous relationships.

$$V_{\mathrm{d}}=V_{\mathrm{ds}}-(R_{\mathrm{s}}+R_{\mathrm{d}})I_{\mathrm{d}}, \tag{18}$$

$$V_{\mathrm{g}}=V_{\mathrm{eff}}-R_{\mathrm{s}}I_{\mathrm{d}}, \tag{19}$$

$$I_{\mathrm{d}}=I_{\mathrm{ds}}-\left(V_{\mathrm{d}}/R_{\mathrm{p}}\right). \tag{20}$$

The resistances "R_{s} and R_{d}" are obtained from the following expressions:

$$R_{\mathrm{s}}=\frac{L_{\mathrm{gs}}}{qZaN_{\mathrm{d}}\mu_0}+R_{\mathrm{os}}, \tag{21}$$

$$R_{\mathrm{d}} = \frac{L_{\mathrm{gd}}}{qZaN_{\mathrm{d}}\mu_0} + R_{\mathrm{od}}. \tag{22}$$

where L_{gs} and L_{gd} are the distances between the gate and source, and the gate and drain respectively. R_{os}, R_{od} give the resistance of the Ohmic contact of the source and the drain respectively.

The current expressions are rewritten again as follows:

$$I_{\mathrm{d}}\left(V_{\mathrm{d}}, V_{\mathrm{g}}, R_{\mathrm{s}}, R_{\mathrm{d}}\right) = I_{\mathrm{p}} B_1 \left[\frac{V_{\mathrm{d}} - (R_{\mathrm{s}} + R_{\mathrm{d}}) I_{\mathrm{d}}}{V_{\mathrm{p}}} - \frac{2}{3}\left(\frac{V_{\mathrm{bi}} - V_{\mathrm{eff}} + V_{\mathrm{d}} - R_{\mathrm{s}} I_{\mathrm{d}}}{V_{\mathrm{p}}}\right)^{3/2} + \frac{2}{3}\left(\frac{V_{\mathrm{bi}} - V_{\mathrm{eff}} + R_{\mathrm{s}} I_{\mathrm{d}}}{V_{\mathrm{p}}}\right)^{3/2}\right]. \tag{23}$$

Linear regime:

$$I_{\mathrm{d}}\left(V_{\mathrm{d}}, V_{\mathrm{g}}, R_{\mathrm{s}}, R_{\mathrm{d}}\right) = I_{\mathrm{p}} \left[1 - \left(\frac{V_{\mathrm{bi}} - V_{\mathrm{eff}}}{V_{\mathrm{p}}}\right)^{1/2}\right] . \left[\frac{V_{\mathrm{ds}} - (R_{\mathrm{s}} + R_{\mathrm{d}}) I_{\mathrm{d}}}{V_{\mathrm{p}}}\right]. \tag{24}$$

Saturated regime:

$$I_{\mathrm{dsat}} = I_{\mathrm{p}} B_2 \left[\frac{1}{3} - \left(\frac{V_{\mathrm{bi}} - V_{\mathrm{g}} + R_{\mathrm{s}} I_{\mathrm{d}}}{V_{\mathrm{p}}}\right) + \frac{2}{3}\left(\frac{V_{\mathrm{bi}} - V_{\mathrm{eff}} + R_{\mathrm{s}} I_{\mathrm{d}}}{V_{\mathrm{p}}}\right)^{3/2}\right] \text{ with : } B_1 = B_2 = \frac{\left[1 + \{(v_{\mathrm{s}}(V_{\mathrm{ds}} - (R_{\mathrm{s}} + R_{\mathrm{d}}) I_{\mathrm{d}}))\}^3 / \mu_{\mathrm{n}} L_3 E_{\mathrm{c}}{}^4\right]}{\left[1 + (V_{\mathrm{ds}} - (R_{\mathrm{s}} + R_{\mathrm{d}}) I_{\mathrm{d}}) / L E_{\mathrm{c}}\right]}. \tag{25}$$

Supplementary Section 3

The current density in the canal can be estimated by the Ohm law as below[5]:

$$J_x = (x, y, z) E_x. \tag{26}$$

where $\sigma(x, y, z)$ was the canal conductivity, $\rho(x, y)$ was the fixed charges density in the depopulated region, and the mobile charges density in the conductive channel region at a point (x, y, z) for an n-channel transistor was given by $-\rho(x, y)$:

$$J_x = \rho(x, y) \mu(E_x), \tag{27}$$

where $\mu(E_x)$ was the carrier mobility.

The drain current, counted positively in the sense drain–source, was obtained by integrating $(-J_x)$ on all the conductive sections of the channel:

$$I_{\mathrm{d}} = -\int_s J_x \mathrm{d}s = -\int_s \rho(x, y) \mu(E_x) \mathrm{d}s. \tag{28}$$

The drain current depended on the electric field $E_x(x)$, the amount of charges $Z\rho(x, y)$ (where, Z is the channel width) and the carrier mobility $\mu(E_x)$ between the gate and the drain. Hence, the drain current was calculated as:

$$I_{\mathrm{d}} = E_x(x) \mu(E_x) \int_h^a z\rho(x, y) \mathrm{d}y = z\mu(E_x) E_x(x) \int_h^a \rho(x, y) \mathrm{d}y, \tag{29}$$

$$I_{\mathrm{d}} = -z\mu(E_x) E_x [Q(a) - Q(h)], \tag{30}$$

where h is the channel depth, and a is the maximum depth.

Supplementary Section 4

Islam *et al*. model [Solid State Electron, 2004, 48, 1111–1117] was a seven-parameter nonlinear current–voltage (I–V) characteristics model to develop the sub-micrometre range GaAs MESFETs. In Islam's model, the effects of both drain-to-source voltage, V_{DS}, and gate-to-source voltage, V_{GS}, on the output conductance, g_d, have been incorporated. In our model, based on the interface states of the metal–semiconductor junction, a differential equations system has been designed by formulizing the seven-parameters (e.g. the gate-to-source voltage, drain-to-source voltage, drain current, transconductance, conductance, the capacitance of gate–source and gate–drain). Also, the effect of the parasitic resistances of the source and drain (R_s & R_d) was taken into consideration in the development of this model.