A Surface-Potential Based Compact Model for GaN HEMTs Incorporating Polarization Charges

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High electron mobility transistors (HEMTs) based on III-nitride semiconductor heterostructures are being actively pursued for high-voltage and high-speed microwave applications [1]. As discrete GaN transistors move towards integration in circuits, a compact model for device operation is highly desirable to aid systematic design. GaN HEMTs differ from Silicon and other III-V FETs through the presence of high density polarization-induced sheet charges at heterostructure interfaces. Till date, no clear method exists to incorporate such polarization charges into compact modeling of HEMTs. We introduce a method for incorporating polarization sheet charges into compact modeling in transistors. The Poisson equation is solved directly with a Dirac-delta function sheet charge at the heterojunction to obtain an analytical equation for the surface potential. This surface potential is then used to calculate the HEMT characteristics. Thus, the results of this work for the first time make an explicit connection between the material properties of the HEMT heterostructure with a surface potential based compact model through the polarization sheet charge. Furthermore, we have extended the intrinsic model by including field-dependent mobility and velocity saturation. The developed model should prove helpful in designing of devices and circuits.

Fig. 1(a) depicts the cross section of a GaN HEMT with a gate barrier of thickness t_b, an unintentionally doped GaN layer of thickness t_{GaN} of doping N_d sitting on a semiinsulating substrate, and source and drain contact regions. The self-aligned device structure has a gate length (= source-drain separation) of L. The regions of interest in the compact model include the GaN and the barrier layers. We denote the local potential in this region as $\psi(x, y)$ with the axes shown in Fig. 1(a). The potential variation along the x direction is retained, and the y direction variation is parameterized in terms of the boundary conditions $\psi(x, 0) = 0$ and $\psi(x,L) = V_{ds}$. The local potential is then governed by the Poisson equation,

$$\frac{\partial^2\psi(x)}{\partial x^2} = -\frac{q}{\epsilon_s}\left[p(x) - n(x) + N_d^+ + \sigma_\pi\delta(x - x_0)\right], \quad (1)$$

Where all symbols have their usual meanings. The polarization sheet charge σ_π is explicitly included in the form of a Dirac-delta function located at $x = x_0$, which is precisely the location of the heterojunction. The charge-diagram and the resulting potential are shown schematically in Fig. 1(b) and (c). The potential at the heterojunciton $\psi(x_0) = \psi_s$ is thesurface potential. We note the relation $\sigma_\pi \int_{x_0-\delta}^{\infty}(d\psi/dx)\delta(x - x_0)dx = \sigma_\pi \times d\psi/dx|_{x_0-\delta}$. Here δ is chosen infinitesimally close to the heterojunction, but on the barrier side to include the polarization sheet charge. The potential at the metal gate is $\psi_G = V_{gs}$-V_p $=V_{gp}$, where V_p is the pinch-off voltage. Since there are no charges in the barrier, $d\psi/dx|_{x_0-\delta} = (\psi_s - V_{gp})/t_b$, and Eq.1 may be solved to the closed form,

$$\frac{1}{2}\left(\frac{V_{gp}-\psi_s}{t_b}\right)^2 + \frac{q\sigma_\pi}{\epsilon_s}\left(\frac{V_{gp}-\psi_s}{t_b}\right) + \frac{q}{\epsilon_s}\left[\psi_s N_d + v_t p_0(1 - e^{-\frac{\psi_s}{v_t}}) - v_t N_d e^{-\frac{V}{v_t}}(e^{\frac{\psi_s}{v_t}} - 1)\right] = 0. \quad (2)$$

Eq. 2 is the main result of this work. It is a closed formequation for the surface potential in GaN HEMTs with an explicit appearance of the polarization charge σ_π. The surface potential ψ_s of Eq. 2 depends on the localpotential V, which assumes values $V = 0$ at the source end, and $V = V_{ds}$ at the drain end of the HEMT. To illustrate the dependence of ψ_s on the gate and drain biases in a HEMT, we choose a representative polarization charge $\sigma_\pi = 10^{13}/\text{cm}^2$ at the heterojunction, $N_d = 10^{16}/\text{cm}^3$, t_b = 12 nm, $\epsilon_s = 9\epsilon_0$, and T = 300 K fixes the intrinsic carrier concentration n_i. The resulting surface potential is plotted in Fig. 2(a) as a function of the gate voltage for various values of V. The on- and off-state drain currents are easily obtained with knowledge of the surface potential [4]. Using mobility degradation due to normal electric field and velocity saturation due to high lateral field in the channel, the I-V characteristics can be written into following expression [3], $\mathrm{I_d} = \mathrm{I_d^{acc/dep}}/(\mathrm{G_{avg}}/2).[\sqrt{1+\Gamma^2} + \ln(\Gamma + \sqrt{1+\Gamma^2})/\Gamma]$,where $\Gamma = (\mu_0.\Delta\psi_s)/(v_{sat}.L.G_{avg})$ and $G_{avg} = 1 + a.F_{avg}^2 + b.F_{avg}^{1/3}$ with $F_{avg} = (1/2).[c_b.(V_{gp} - \psi_{savg}) + qN_d t_{GaN}]/\epsilon_s$ and $\psi_{savg} = (\psi_{sS} + \psi_{sD})/2$.

Using the model, we first calculate the intrinsic device characteristics of Al(Ga,In)N/GaN HEMT with constant mobility and without velocity saturation effects as shown in Fig. 2(b). Then we calculate device characteristics with mobility degradation and velocity saturation effects as shown in Fig. 2(c). Fig. 3(a) plots the transfer curves of intrinsic model with constant mobility and with field dependent mobility for drain bias of 4V. The magnitude of current density becomes lower due to mobility reduction and velocity saturation of electrons as compared to intrinsic model. The intrinsic transconductance $g_m = \partial I_d/\partial V_{gs}$ at different V_{gs} are calculated and shown in Fig. 3(b). Note the sharp drop in g_m beyond the peak, and the sub-linear increase of the drain current with gate bias. The model captures most observed properties in GaN HEMTs.

In summary, a compact model for GaN HEMTs that explicitly captures the effect of polarization charges at heterojunctions has been developed. The model should be useful for both microwave as well as digital devices.

[1] Mishra et al, Proc. IEEE, 90, 1022 (2002), [2] Taur et al, Fundamentals of Modern VLSI Devices, 2nd ed. (2009),
[3] Langevelde et al., Physical background of MOS model 11, 2003/00239, [4] Nassar et al., IEEE Trans. on Electron Dev., 56, 1974 (2009).

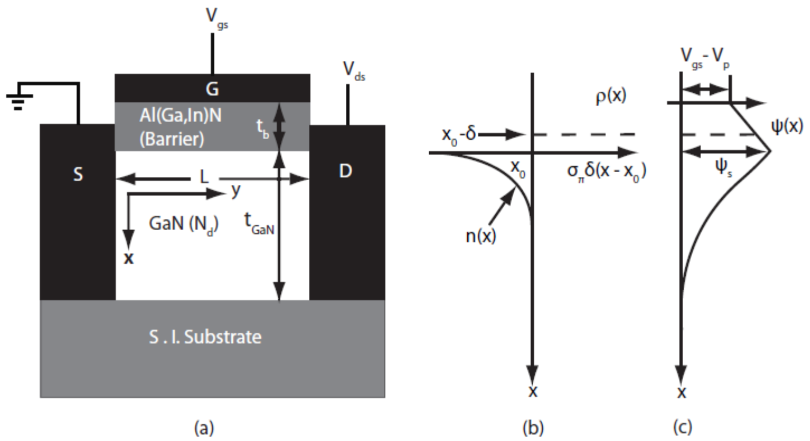

Fig. 1: (a) Al(Ga,In)N/GaN HEMT cross section with relevant parameters. (b) Charge distribution $\rho(x)$ with polarization sheet charge σ_π at the heterojunction and mobile charge $n(x)$. (c) The potential distribution $\psi(x)$. Thepotential at the heterojunction is the surface potential ψ_s

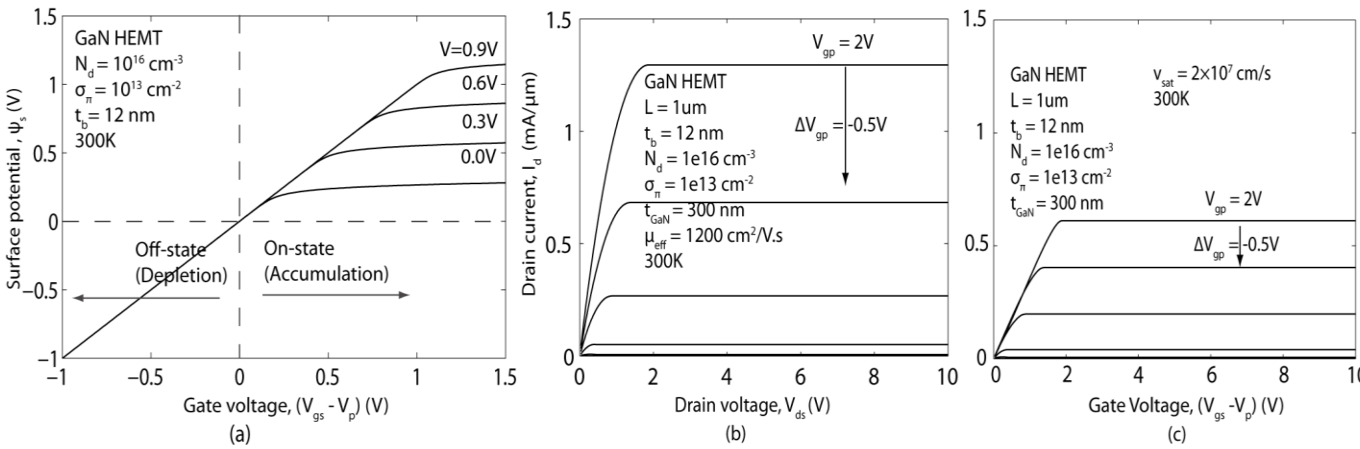

Fig. 2:(a) The surface potential ψ_s as a function of gate voltage for differentlocal channel potentials V depicting the depletion and the accumulation regions, (b) The calculated drain current I_d versus drain voltage V_{ds} for different effective gate voltages $(V_{gs}$ $-V_p)$ for a GaN HEMT without velocity saturation effect, (c) Output characteristics (I_d-V_{ds}) show the degradation of saturation current due to mobility reduction and velocity saturation effects of mobile electrons in the channel.

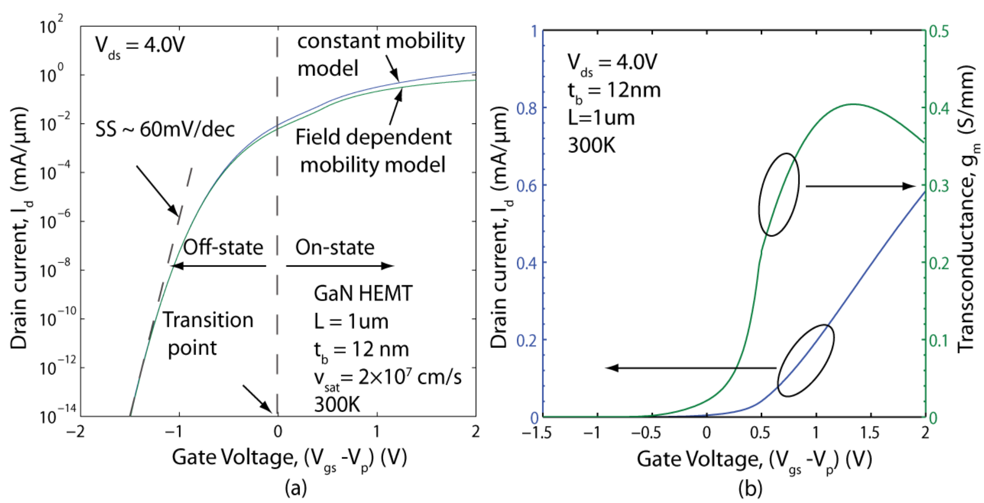

Fig. 3: (a) Calculated transfer curves depicting the drain current versus effective gate voltage, V_{gs} - V_p for drain biases V_{ds} = 4.0V with constant mobility and field dependent mobility of electrons in the channel. Field dependent mobility model shows the drain current reduction than the constant mobility model, (b) The net drain current and transconductance g_m versus V_{gs}-V_p. Transconductance decreases from peak value due to mobility reduction with normal electric field and velocity saturation of electron due to high drain bias is shown based on this model.