Composite Sub-surface Model for RF GaN-HEMTs

***Abstract*—A new approach to RF compact modeling with a "sub-surface model" for the nonlinear substrate current/charge (rather than the conventional linear *R*/*C* sub-circuit) is proposed for GaN-HEMTs, which is also extended to the source/drain (S/D) access regions as ungated HEMTs. By comparison with numerical device *S*-parameters, preliminary results show that the composite sub-circuit model demonstrates good matching with scalable dc-biases as well as gate and S/D lengths and body doping concentrations. Model verification with experimental devices (105nm and 40nm) is also given. It proves to be a useful approach to RF circuit design and optimization with physical and scalable predictability.**

Keywords—compact modeling, HEMT, RF, sub-circuit

It is well known that numerical device simulations provide terminal current/charge solutions as the integral through the body of the 2D (3D) device; and its local variations with respect to voltages (conductances and capacitances) at any frequencies. A surface-potential-based compact model (CM) usually captures the intrinsic-channel terminal current/charge while ignoring the small current in the substrate (e.g., punch-through) and capacitances at low frequencies. At RF frequencies, these "missing" elements are modeled by constructing a (linear) *R*/*C* sub-circuit, whose values are fitted to the measured (or numerical) *S*-parameters. However, these *R*/*C* values need to be re-fitted at different dc biases (Q-point).

We propose to extend our developed surface-potential-based GaN-HEMT model to the sub-surface in place of the *R*/*C* sub-circuit, which includes the essential behaviors of the (surface) HEMT to represent the (trans-) conductances (1/*R*) and capacitances (*C*) in the substrate that are also Q-point scalable. It is also extended to the S/D access regions for geometry/doping scalability. The composite RF sub-circuit for GaN-HEMT is shown in Fig. 1.

Preliminary results for the model playback of the S_{22} parameters are shown in Fig. 2 in comparison with the numerical data, after calibrating the CM with the numerical dc characteristics. It showed good match at different V_{gs} biases and L_{gs}/L_{gd} ratios without re-fitting.

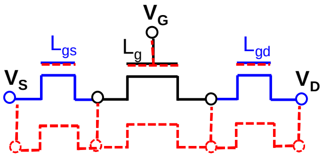

Fig. 1. The proposed RF composite sub-circuit including a sub-surface HEMT beneath the intrinsic (surface) HEMT, and extended to the (ungated) S/D access regions.

Our GaN-HEMT model has also been calibrated to the experimental devices of 105nm and 42nm gate lengths [1]. With such a scalable model, one can easily evaluate optimal RF figures-of-merits, such as the cut-off frequency f_T, through its unity current-gain definition ($\beta = |i_{out}/i_{oin}| = 1$) with ac analysis at peak g_m biasing Q-points. The model results are shown in Fig. 3, which demonstrate good prediction for the measurement data [1]. One can also perform quick f_T evaluations through the equation ($f_T = g_m/2\pi C_{gg}$) at any Q-points without running full ac analyses.

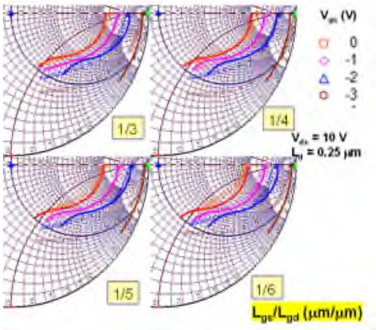

Fig. 2. Smith charts for S_{22}: CM playback (lines) of the L_g = 0.25 µm HEMTs with 4 L_{gs}/L_{gd} ratios as indicated compared with the numerical data (symbols) for varying V_{gs} = 0, –1, –2, –3 V (V_{ds} = 10 V).

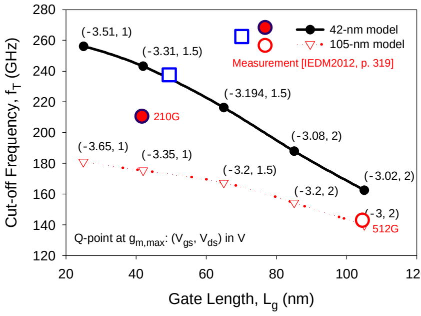

Fig. 3. f_T vs. L_g predictions as obtained from model ac analyses at maximum g_m biasing Q-points indicated for the L_g = 105 nm and 42 nm HEMTs. Measurement data [1] of the corresponding devices are also shown.

The proposed sub-surface approach to RF modeling, in place of the conventional *R*/*C* sub-circuit in the substrate network, not only demonstrates bias, geometry, and doping scalability as well as easy implementation, it is also the correct approach to modeling the intrinsic device (surface + substrate) by the model developer, rather than building a user sub-circuit based on an "incomplete" intrinsic CM to match the measured (or numerical) *S*-parameters. *R*/*C* elements can be added in the sub-circuit to capture the fringing capacitance. The proposed novel methodology can be generalized to MOSFET RF compact modeling.

REFERENCE

[1] U. Radhakrishna, L. Wei, D.-S. Lee, T. Palacios, D. Antoniaddis, "Physics-based GaN HEMT transport and charge model: experimental verification and performance projection," *IEDM Tech. Dig.*, 2012, pp. 319–322.