A Genetic-Neural-Network Modeling Approach for Self-Heating in GaN High Electron Mobility Transistors

Anwar Jarndal

***Abstract*—**In this paper, a genetic-neural-network (GNN) based large-signal model for GaN HEMTs is presented along with its parameters extraction procedure. The model is easy to construct and implement in CAD software and requires only DC and S-parameter measurements. An improved decomposition technique is used to model self-heating effect. Two GNN models are constructed to simulate isothermal drain current and power dissipation, respectively. The two model are then composed to simulate the drain current. The modeling procedure was applied to a packaged GaN-on-Si HEMT and the developed model is validated by comparing its large-signal simulation with measured data. A very good agreement between the simulation and measurement is obtained.

***Keywords*—**GaN HEMT, computer-aided design & modeling, neural networks, genetic optimization.

I. Introduction

TODAYS, GaN HEMT transistors are becoming the most appropriate technology for high power amplifier (HPA) design [1]. This accordingly increases the need for rigorous modeling of the electrical and electro-thermal behavior of GaN devices. In the last decade, many models for GaN HEMT devices have been published [2]–[5]. Most of these models are based on analytical or table-based modeling techniques. The analytical modeling technique is computationally efficient (convergence and prediction); however, it is technology dependent and higher efforts is required to formulate the expression and optimize the fitting parameters. The table-based modeling technique is technology independent and more accurate than the analytical one but it has lower convergence rate and it has no prediction capability. In this paper, genetic neural networks as a modeling technique for GaN devices will be investigated. This model "learn" the relationship between input and output from the measured data, and then it can efficiently predict the output value for any input value [6]. This modeling approach is accurate and there is no assumption of particular analytical functions (black-box modeling). The model prediction capability can also be improved by using a knowledge-based approach to choice a suitable activation function.

Self-heating due to high power dissipation represents the main challenge of GaN HEMTs power transistors especially for those on Si Substrate. This regenerative process degrades the electrons saturation velocity and thus reduces the drain current [7]. The self-heating significantly impacts the device performance especially under static and quasi-static operation. At higher frequency this effect is reduced, because in this case, the input signal is not slow enough to heat up the device.

An efficient approach will be presented in this paper to simulate the self-heating based on DC IV measurements in two regions (low and high power dissipation areas) of operation. The general behavior of the drain current without self-heating (isothermal condition) is modeled by using single-hidden layer GNN model based on the measurements of the 1st zone of negligible power dissipation. Similar GNN model is then used to simulate variation of the power dissipation with the gate and drain voltages in the 2nd zone of high power dissipation. Both models are then combined to simulate the drain current and its associated self-heating effect.

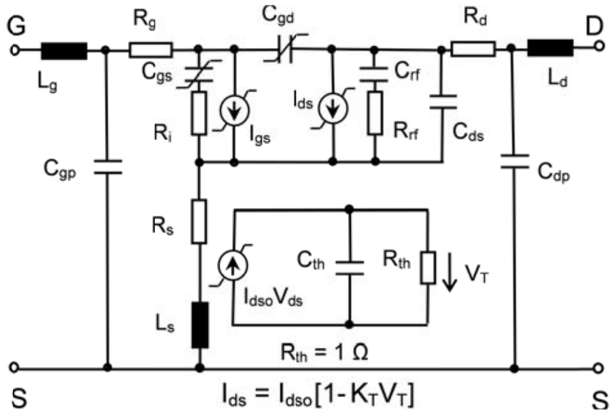


Fig. 1 Large-signal equivalent circuit model for GaN HEMTs including self-heating and output conductance dispersion effects

II. Equivalent Circuit Model

The device is modeled by the equivalent circuit shown in Fig. 1. The extrinsic RLC of the model represents contact and semiconductor bulk resistances, metallization, bond wire, and package inductances and pad contacts capacitances. The intrinsic part of the model simulates the depletion region capacitances (C_{gs}, C_{gd}, and C_{ds}) and gate and drain (channel) currents I_{ds} and I_{gs}. The model also includes an additional RC branch (C_{rf} and R_{rf}) and a thermal sub-circuit to simulate trapping and self-heating induced dispersion, respectively. The same developed extraction method for the extrinsic and

Anwar Jarndal is with the Electrical and Computer Engineering Department of University of Sharjah, 27272 Sharjah, United Arab Emirates (phone: +971-6-5050928; fax: +971-6-5050872; e-mail: ajarndal@sharjah.ac.ae).

intrinsic elements of the model in [4] has been used. The bias dependency of C_{gd} and C_{gs} has been modeled by simple polynomial and tangent functions, respectively [4].

A genetic neural network based model is used to represent the gate currents. The model topology includes only a single hidden layer with unit biases, as illustrated in Fig. 2. According to this model, the gate current can be expressed as

$$I_{gs} = \sum_{i=1}^{3} w_i\, f\left(w_{1i} V_{gs} + w_{2i} V_{ds} + w_{3i}\right) \quad (1)$$

where V_{gs} and V_{ds} are the intrinsic gate and drain voltages, w_{1i}, w_{2i} and w_{3i} are the input weights and w_i is the output weight. The activation function f(.) equal to $e^{(.)}$ for this case of the gate current. This function is consistent with the typical exponential behavior of the gate current and improves the model accuracy. The model weights are optimized to find the best fitting for measured I_{gs}. As it will be explained in the next section, genetic algorithm optimization is used to find an optimal value for each of the 12 model weights.

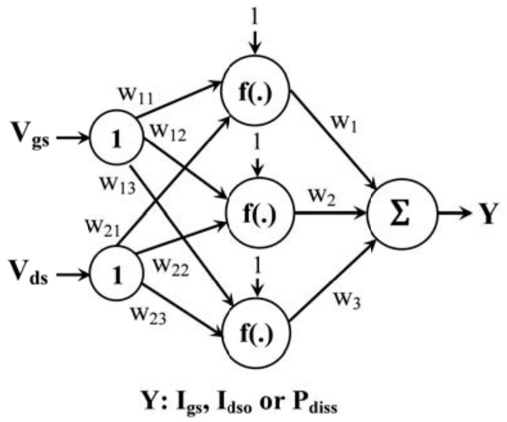


Fig. 2 Topology of the implemented GNN model

The drain current and its inherent self-heating is formulated as:

$$I_{ds} = I_{dso}\left[1 - K_T H_{LP}(\omega) P_{diss}\right]. \quad (2)$$

where I_{dso} is the isothermal current at ambient temperature. K_T is fitting parameter accounts for the device thermal resistance and the temperature dependence of the drain current. The power dissipation P_{diss} is multiplied by low frequency function $H_{Lp}(\omega)$ to simulate the significant self-heating under static and/or quasi-static operation. This term is implemented using the low-pass thermal sub-circuit in the model (see Fig. 1). Fig. 3 shows a schematic of the developed drain current model including the self-heating. Bias dependence of the isothermal drain current is modeled by GNN model of the same topology shown in Fig. 2.

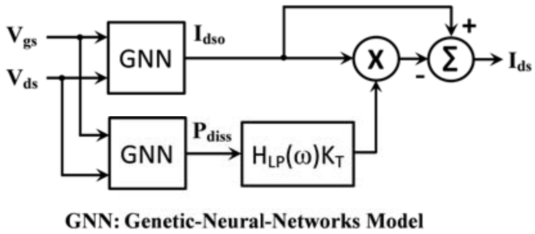


Fig. 3 Schematic of the drain current model

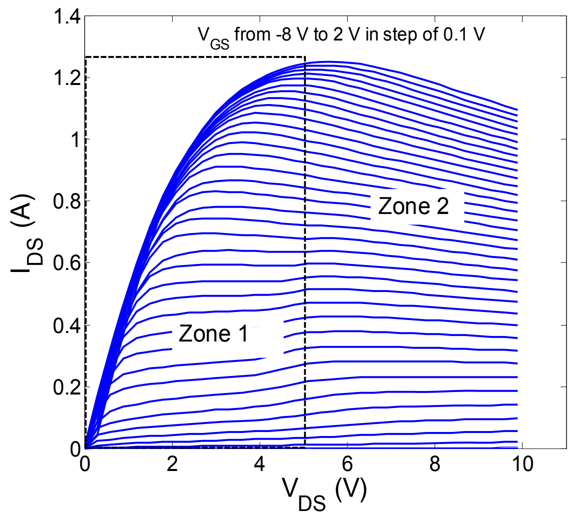


Fig. 4 Measured drain current of packaged GaN HEMT

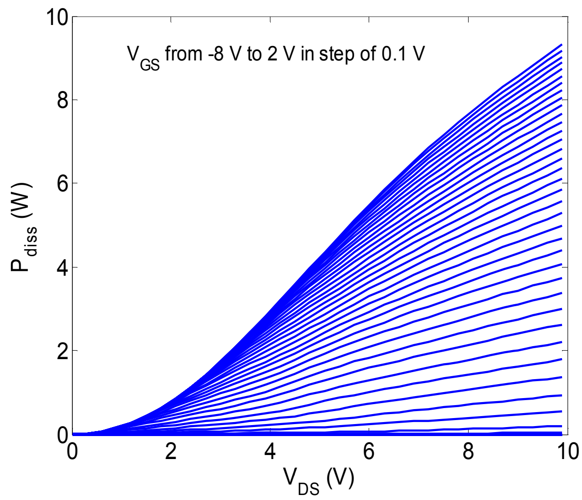


Fig. 5 Measured power dissipation of packaged GaN HEMT

The isothermal current represents the DC IV measurements of self-heating free (negligible power dissipation) in zone 1 (see Fig. 4). The corresponding GNN model can be developed by fitting these measurements. Zone 2 represents the whole IV characteristic including the self-heating affected measurements. The power dissipation ($P_{diss}=I_{ds}V_{ds}$) is calculated over the whole measured IV characteristics as show in Fig. 5. These data of P_{diss} are then modeled using another GNN model of the same topology presented in Fig. 2. The same genetic algorithm based procedure is used to find optimal weights of the model. The predicted P_{diss} passes through low pass filter and scaled by K_T and then multiplied by the predicted I_{dso} to produce $I_{dso}K_TP_{diss}$. This term or value is then subtracted from the original I_{dso} to simulate the reduction in the drain current caused by self-heating.

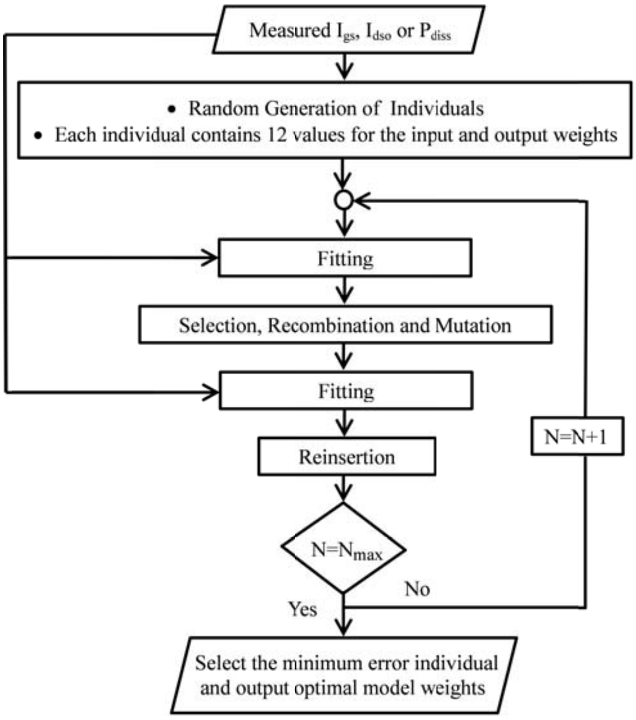
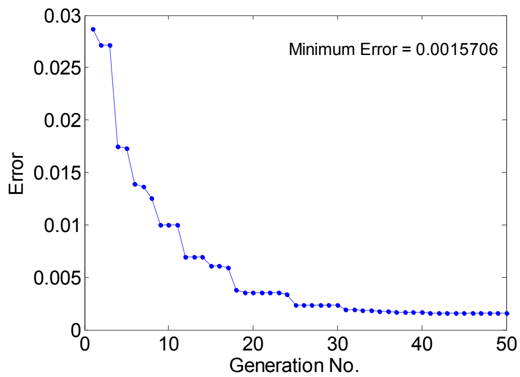


Fig. 6 Flowchart of the neural network weights optimization using genetic algorithm

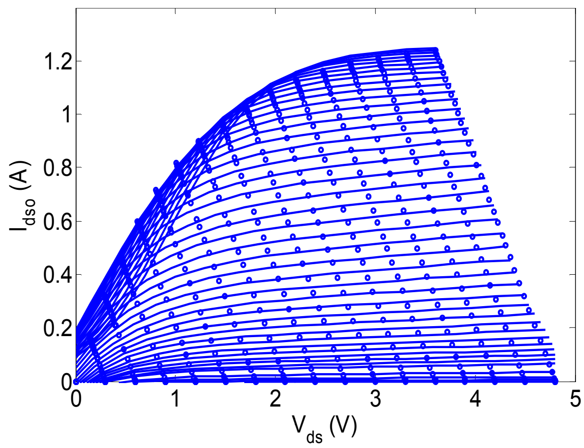
III. Model Parameters Optimization

As it has been mentioned in the last section, genetic algorithm based optimization procedure is used to find optimal values for the 12 weights of the GNN model. The procedure is illustrated by the flow chart in Fig. 6. The optimization process is started by random generation of initial population of individuals. Each individual consists of 12 values (9 for the input weights and 3 for the output weights). These individuals represent the first generation of parents. The individuals are then evaluated by fitting the measurements (I_{gs}, I_{dso} or P_{diss}) and the best (minimum error) 90% out of them are selected to be the parents of the next generations. The selected individuals undergo recombination (crossing)and mutation operations to produce the next generation of offspring. These individuals are then evaluated by fitting the measurements to find those of minimum errors. In the next step of reinsertion, the most error individuals in the old population (parents) are replaced by the selected offspring individuals. The combined individuals will be considered as parents for the next generation and pass through selection, crossing and mutation operations. The optimization process will continue over N_{max} generation to find at the end the minimum error individual and the associated optimal values of the model weights.

This procedure has been applied to DC IV measurements of a packaged GaN HEMT device from Nitronex corporation to determine the optimal weights of the neural network models of the drain and gate currents. The optimization process is started by generating a uniformly distributed random initial population of 1000 individuals. Each individual consists of 12 values (input and output weights). The maximum number of generations is set to 50. The procedure was applied to the first zone of the measured drain current to construct the GNN model of I_{dso}. Fig. 7 (a) shows error variation versus the number of generation during the optimization process of the model weights. Fig. 7 (b) presents the predicted and measured isothermal drain current in zone 1. This process is re-applied on the measurements of P_{diss} in the second zone to determine the optimal weights of the corresponding GNN model. The optimization results are presented in Fig. 8. As it can be seen, the model can efficiently reproduce I_{dso} and P_{diss}.

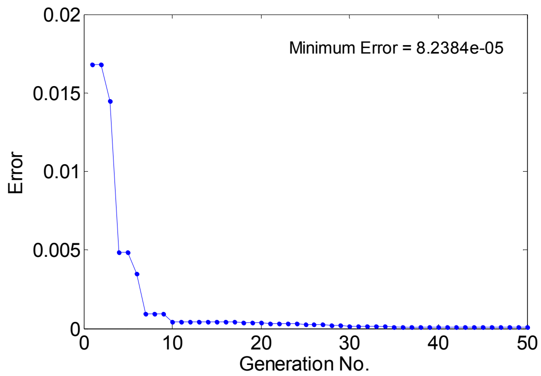


(a)

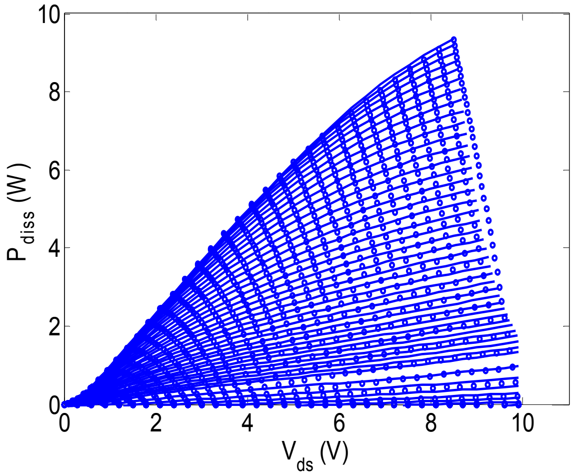


(b)

Fig. 7 (a)Variation of the error with the number of generation during model weights optimization of the isothermal drain current model; (b) Measured (circles) and predicted(lines) isothermal drain current of a packaged GaN HEMT



(a)



(b)

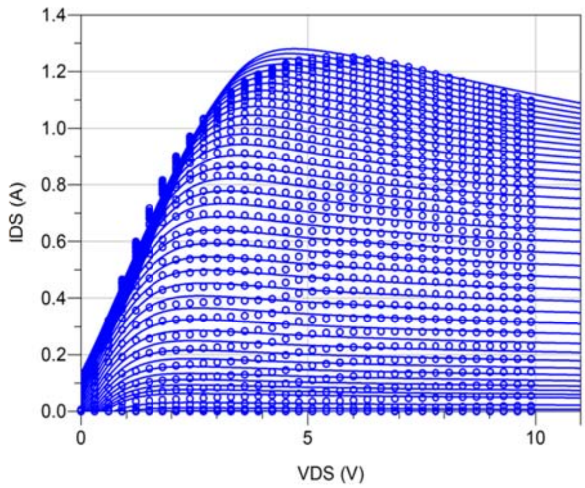
Fig. 8 (a) Variation of the error with the number of generation during model weights optimization of the drain current power dissipation P_{diss}; (b) Measured (circles) and predicted (lines) power dissipation of a packaged GaN HEMT

IV. Model Implementation and Validation

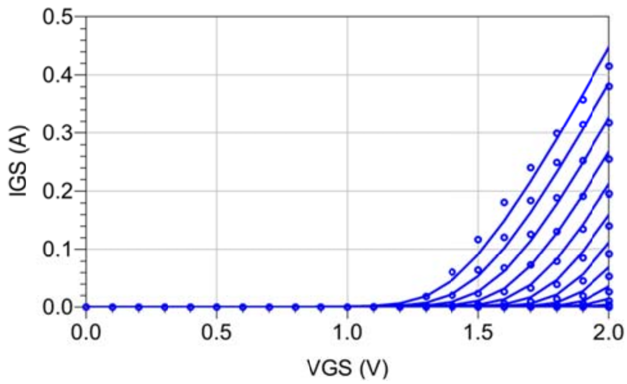
The modeling procedure has been applied to the considered packaged GaN HEMT. The developed large-signal model was implemented in Advanced Design System (ADS®). The extrinsic bias-independent passive elements (see Fig. 1) are represented by lumped elements, while the intrinsic nonlinear part is implemented by a symbolically defined device (SDD) and data access (DAC) components. The GNN model in Fig. 2 can be easily implemented in ADS by

$$\begin{aligned} Y = w_1 f\left(w_{11}V_{ds} + w_{21}V_{gs} + w_{31}\right) \\ + w_2 f\left(w_{12}V_{ds} + w_{22}V_{gs} + w_{32}\right) \\ + w_3 f\left(w_{13}V_{ds} + w_{23}V_{gs} + w_{33}\right) \end{aligned} \tag{3}$$

where f(.) is equal to tanh(.) for I_{dso} and P_{diss}; while it is equal to $e^{(.)}$ for I_{gs}. The implemented model is validated by the DC IV measurements shown in Fig. 9. As it can be seen, the model reproduces the measurements in a very good manner and predicts the drain current in the high power dissipation area. The model has been also validated by single-tone large-signal measurements shown Fig. 10 for the same device. A very good agreement between measurements and simulations can be observed. The model also showed a very good convergence rate and smaller time of simulation with respect to the table-based model reported in [4] for the same device.



(a)



(b)

Fig. 9 Simulated (lines): (a) DC drain current and (b) DC gate current of a packaged GaN HEMT in comparison with measurements (circles)

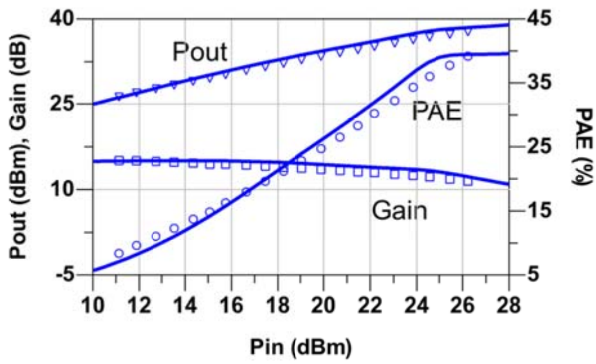


Fig. 10 Measured (symbols) and simulated (lines) output power, gain and efficiency for class-AB operated packaged GaN HEMT in a 50 Ω source and load environment at 2.35 GHz

V. Conclusion

The developed modeling approach showed a very good simulation with higher rate of convergence for GaN HEMTs. The modeling approach can be extended to consider extra anomalies such as kink effect in the drain IV characteristics.

Acknowledgment

The author gratefully acknowledges the support from the University of Sharjah, Sharjah, United Arab Emiratis.

References

[1] U. K. Mishra, L. Shen, T. E. Kazior, and Y.-F. Wu, "GaN-based RF power devices and amplifiers," *Proc. IEEE*, vol. 96, no. 2, February 2008, pp. 287–305.
[2] J.-W. Lee and K. Webb, "A temperature-dependent nonlinear analytic model for AlGaN-GaN HEMTs on SiC," *IEEE Transaction on Microwave Theory and Techniques*, vol. 52, January 2004, pp. 2–9.
[3] Anwar Jarndal and Günter Kompa, "Large-signal model for AlGaN/GaN HEMT accurately predicts trapping and self-heating induced dispersion and intermodulation distortion," *IEEE Transaction on Electron Devices*, vol. 54, no. 11, November 2007, pp. 2830-2836.
[4] Anwar Jarndal, Pouya Aflaki, Renato Negra, Ammar Kouki, and Fadhel M. Ghannouchi, "Large-signal modeling methodology for GaN HEMTs for RF switching-mode power amplifiers design," *International Journal of RF and Microwave Computer-Aided Engineering*, vol.21, no. 1, November 2010, pp. 45-50.
[5] Anwar Jarndal, Asdesach Zena Markos, and Günter Kompa, "Improved modeling of GaN HEMT on Si substrate for design of RF power amplifiers," *IEEE Transactions on Microwave Theory and Techniques*, vol. 59, No.3, March 2011, pp. 644 - 651.
[6] Q. j. Change and K. C. Gupta, Neural networks for RF and microwave design, Norwood, MA: Artech House, 2000.
[7] J. Kuzmík, S. Bychikhin, M. Neuburger, A. Dadgar, A. Krost, E. Kohn, and D. Pogan, "Transient Thermal Characterization of AlGaN/GaNHEMTs Grown on Silicon," *IEEE Transaction on Electron Devices*, vol. 52, no. 8, August 2005.

Anwar Jarndal was born in Zabid, Yemen, in 1973. He received his B.Sc. degree (with honors) in Electronics and Communication Engineering from the Applied Sciences University, Amman, Jordan, in 1998, M.Sc. degree in Communication and Electronics Engineering from the Jordan University of Science and Technology, Irbid, Jordan, in 2001, and Ph.D. degree in Electrical Engineering from the University of Kassel, Kassel, Germany, in 2006. From 1999 to 2001, he was a Teaching Assistant at the Jordan University of Science and Technology. From 2001 to 2003, he was a Lecturer at Hodeidah University, Hodeidah, Yemen. In 2007, he became an Assistant Professor at the Computer Engineering Department of Hodeidah University. In 2008, he was a post-doctoral fellow at Ecole de Technologie Superieure of Quebec University, Montreal, Canada. From 2011 to 2013, he was an assistant professor in the Electrical and Computer Engineering department of the University of Nizwa, Nizwa, Oman. Currently, he is an assistant professor at the Electrical and Computer Engineering Department of University of Sharjah, Sharjah, UAE. His main research interests include modeling of active devices for microwave circuits design. Dr. Jarndal is a member of reviewing boards of many international journals and conferences. He has published more than 40 papers in the field of active devices modeling and RF power amplifiers design.