ATLANTIS PRESS
Advances in Computer Science Research (ACRS), volume 54
International Conference on Computer Networks and Communication Technology (CNCT2016)

A Scalable Equivalent Circuit Model for Gan On-Chip Transmission Lines

Ming-hui ZHANG[1], Wei-liang HE[1, *],Han-sheng WANG[1] and Lu TANG[1]

[1] School of Information Science and Engineering, Southeast University, Nanjing 211189, China

*Email:213142011@seu.edu.cn

Keywords: GaN on-chip transmission line; Equivalent circuit model; Characteristic function; Scalability.

Abstract. This paper presents a scalable equivalent circuit model of GaN on-chip transmission lines. The equivalent circuit model is derived and verified to characterize the frequency-dependent parameters at a range of DC to 40 GHz accurately. Characteristic function approach is utilized to extract all the model parameters properly. The model is validated to be well-fitted and scalable by comparing the theoretical model simulation and electromagnetic simulation in the form of scatter parameter.

Introduction

Due to the rapid development of integrated circuit technology and the huge consumer demand of electronic products, the design of integrated circuit presents more requirements on the stability under the circumstance of high frequency and big power.

GaN process is a thriving wide bandgap semiconductor process satisfying the new requirements in the integrated circuit design. Lately, GaN process is applied in RF integrated circuits with high frequency and big power such as power amplifier [1], and cavity oscillator [2]. Accordingly, many researchers pay more attention on the characteristics of devices made from GaN process. So far, much advancement has been made about active devices, not only in effects like drain current instability [3] and effect of fringing capacitance [4] but also in modeling like the equivalent model of GaN HEMT [5,6]. However, the lack of modeling of passive devices, especially transmission lines, caused much trouble in actual circuit simulation, reflecting in the difference between pre-simulation and post-simulation.

Transmission line modeling is a continuous topic as the integrated circuit technology updates. Nowadays, a number of novel processes are employed in integrated circuit design, which contributes to many successful explorations both in extending new fields, like folded waveguide circuits [7] and noisy electromagnetic media [8], and in deepening previous research, like current distributive effects [9,10]. Transmission line is commonly equivalent to a network of RLGC based on Telegrapher's Equations while the value of R, L, G and C is related to frequency. Based on the basic model, two different ideas are presented. Employing complex circuit topology to feature parasitic effects at high frequency is a conventional idea with difficulty in assuring the circuit topology. Introducing frequency-dependent functions to modeling can ease the difficulty but lack of scalability.

The transmission line studied is based on the GaN process. The devices are laid out over the GaN compound substrate with the cross section shown in Fig. 1.

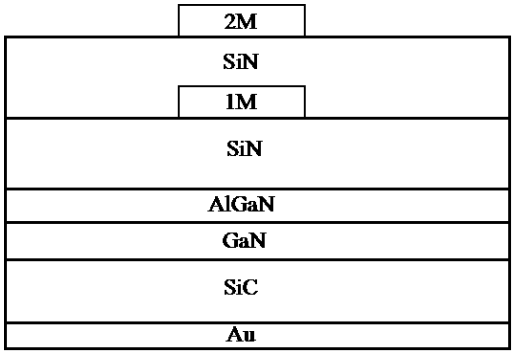

Fig. 1. The cross section of GaN process

This paper is aimed to establish a scalable equivalent circuit model for on-chip transmission line based on GaN process to characterize its frequency-dependent behavior over a wide frequency range from DC up to 40 GHz. Meanwhile, all the parameters are extracted by employing characteristic function approach. The model validation is carried out by comparing theoretical model simulated and electromagnetic simulated scattering parameters.

Model Establishment

Based on the previous research on on-chip interconnects [11] and MMIC semiconductor process [12], the equivalent circuit model shown in Fig. 2 is established to characterize the GaN on-chip transmission lines.

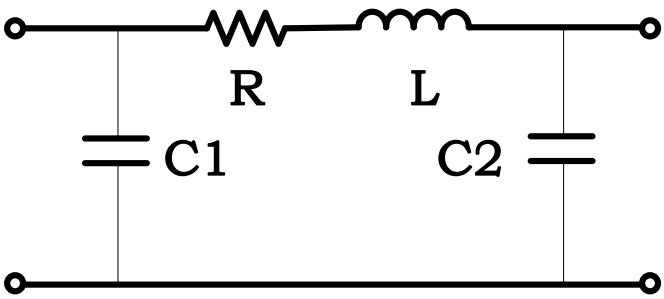

Fig. 2. The equivalent circuit model for GaN on-chip transmission lines

R is to represent the resistance and L is to represent self-inductance. C_1 and C_2 represent the capacity of the GaN compound substrate. Due to the insulation of the substrate, the leakage can be neglected.

Parameter Extraction

The parameter extraction is carried out based on a sample of GaN on-chip transmission lines with the length of 100μm using characteristic function method.

The process is started with the series part. According to the nature of π-type circuit, the following two characteristic function are presented to extract R and L on the basis of Y parameter of the network.

$$f_1(\omega) = \frac{1}{real(-Y_{12})} = \frac{R^2 + \omega^2 L^2}{R} = \frac{L^2}{R}\omega^2 + \mathrm{R} \tag{1}$$

$$f_2(\omega) = \frac{\omega}{\mathrm{imag}(-\mathrm{Y}_{12})} = -\omega\frac{R^2+\omega^2L^2}{\omega L} = -\omega^2\,\mathrm{L} - \frac{R^2}{L} \tag{2}$$

From the linear regression of $f_1(\omega)$-ω^2 and $f_2(\omega)$-ω^2, R and L can be extracted by the intercept of the linear fitting of $f_1(\omega)$ and the slope of the linear fitting of $f_2(\omega)$. The linear fitting figures and extracted results are shown in Fig. 3 and Fig. 4.

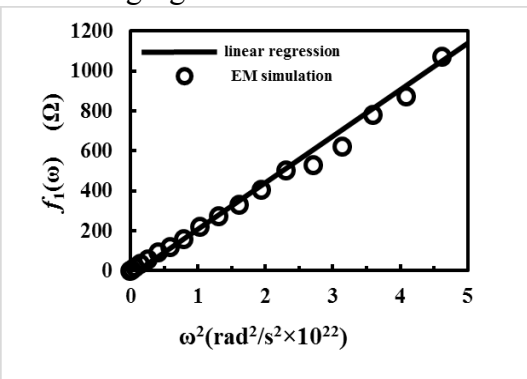

Fig. 3. The linear fitting figure of f1 (ω)

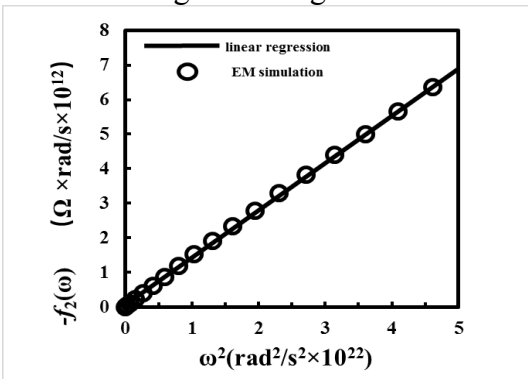

Fig. 4. The linear fitting figure of f2 (ω)

Next is the shunt part. Since the shunt part only contains a capacitor, C_1 and C_2 can be easily extracted from Y parameter of the network.

$$f_3(\omega) = \mathrm{imag}(\mathrm{Y}_{11}+\mathrm{Y}_{12}) = \omega C_1 \tag{3}$$

$$f_4(\omega) = \mathrm{imag}(\mathrm{Y}_{21}+\mathrm{Y}_{22}) = \omega C_2 \tag{4}$$

From the linear regression of $f_3(\omega)$-ω and $f_4(\omega)$-ω, C_1 and C_2 is equal to the slope of the linear fitting of $f_3(\omega)$ and the slope of the linear fitting of $f_4(\omega)$ The linear fitting figure and extracted results are shown in Fig. 5 and Fig. 6.

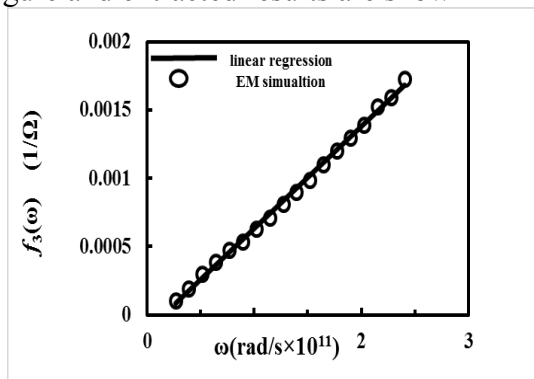

Fig. 5. The linear fitting figure of f3 (ω)

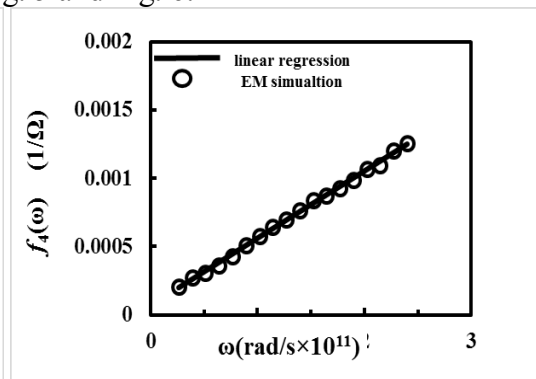

Fig. 6. The linear fitting figure of f4 (ω)

Finally, according to all the process presented above, every parameter can be extracted precisely in the model shown in Fig. 2. All the extracted results are listed in Table 1.

Table 1. The extracted results of model parameters

Model Parameters	Extracted Results
R	0.809Ω
L	0.137nH
C_1	6.34fF
C_2	5.42fF

Model Validation

Since the equivalent circuit model of GaN on-chip transmission line has been established with all the parameters extracted, the model will be validated by theoretical model simulated and electromagnetic simulated scattering parameters obtained by EM simulation software. The validation will be conducted according to two parts, with regard to validity and scalability respectively.

In the first part, the validity of the model will be tested through the comparison between theoretical model simulation and EM simulation of the sample whose length is 100μm.

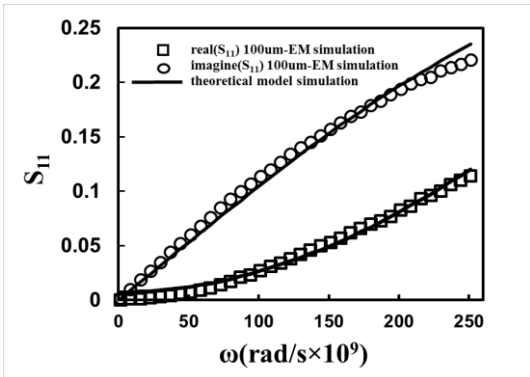

Fig. 7. The figure of S_{11} (l=100μm)

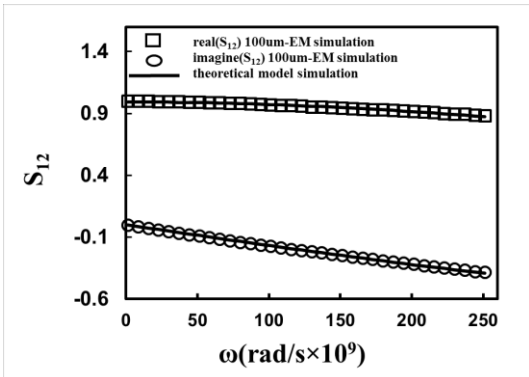

Fig. 8. The figure of S_{12} (l=100μm)

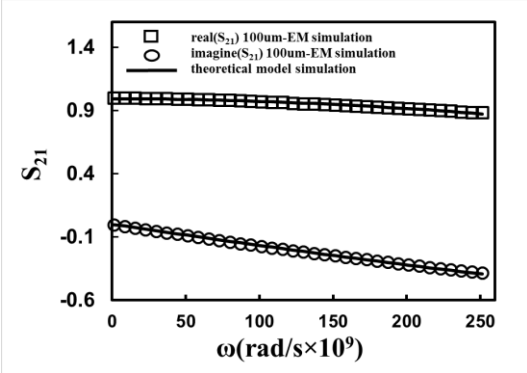

Fig. 9. The figure of S_{21} (l=100μm)

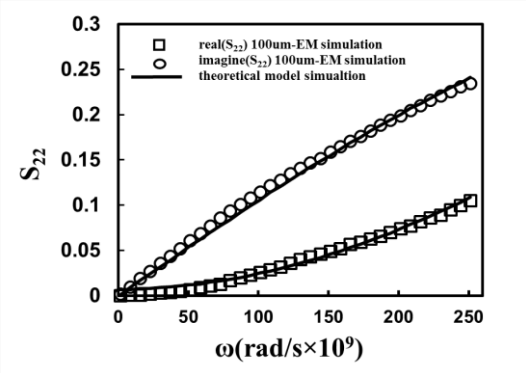

Fig. 10. The figure of S_{22} (l=100μm)

Seen from Fig.7 to Fig.10, the simulation line fits the EM simulated data point well in S parameter, proving that the model can characterize the frequency-dependent behavior of GaN on-chip transmission line over a frequency range.

Anchored in the excellent simulation results in the first part, the scalability will be tested in the second part. The test will be conducted by examining the simulation results of samples whose lengths are in multiples of 100μm. On account of the simple structure of the model, parameter scalability principle can be adopted instead of cascade scalability principle.

Based on scalability principle [13], with regard to samples with the length of N times 100μm, the model parameter can be calculated accordingly as follow.

$$R_N = NR \tag{5}$$

$$L_N = NL \tag{6}$$

$$C_{1N} = NC_1 \tag{7}$$

$$C_{2N} = NC_2 \tag{8}$$

To validate the scalability of the model, samples with the length of 200μm is taken as an example of scalability. The model parameters can be doubled according to the scalability principle mentioned and the theoretical simulation is compared with the EM simulated scatter parameters of samples with the length of 200μm.

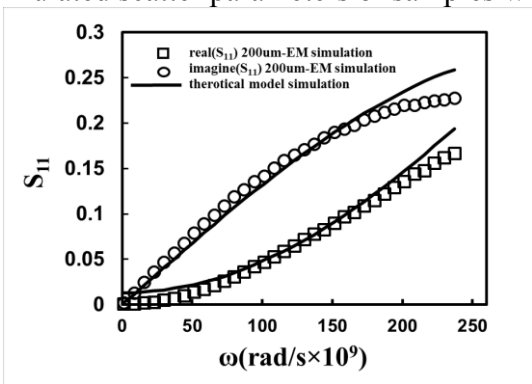

Fig. 11. The figure of S_{11} (l=200μm)

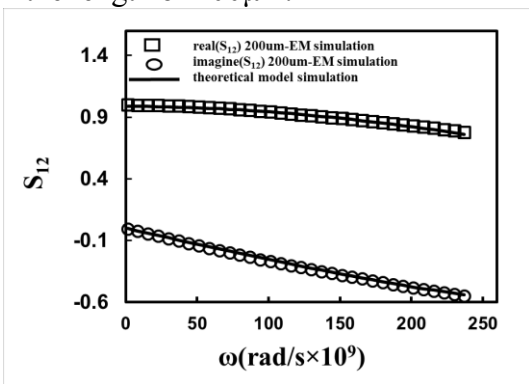

Fig. 12. The figure of S_{12} (l=200μm)

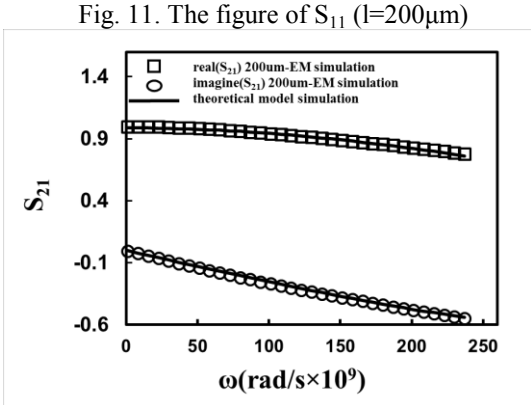

Fig. 13. The figure of S_{11} (l=200μm)

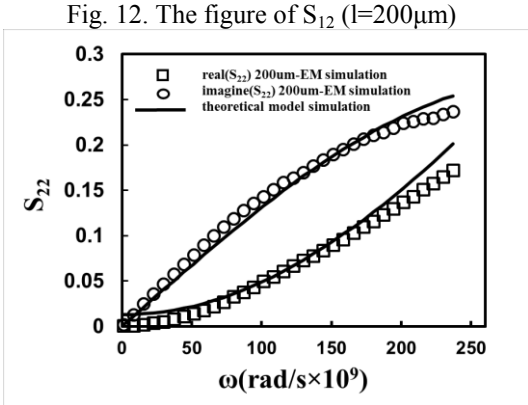

Fig. 14. The figure of S_{12} (l=200μm)

Seen from Fig.11 to Fig.14, the simulation line is in line with the EM simulated data point well in S parameter, proving that the model is scalable based on the scalability principle mentioned. The nature of scalability makes the model possible to be applied in real circuit design. Although the scalability may deteriorate when the frequency is higher or the scale is bigger, it can be of great help in the design of GaN millimeter wave integrated circuit.

Conclusions

In the paper, a scalable equivalent circuit model for on-chip transmission line based on GaN process is presented and validated in the frequency range from DC up to 40 GHz. The model consists of four main elements and all the parameters in the model is extracted by characteristic function approach. The model is tested by comparing theoretical model simulated and EM simulated scattering parameters and proves to be valid and scalable.

As GaN process is a thriving semiconductor technology and on-chip transmission line is a basic structure in the integrated circuit, the model established will be valuable for GaN process research and GaN millimeter wave integrated circuit design.

Acknowledgement

This research was financially supported by the National Natural Science Foundation of China (No.61674036) and Southeast University Teacher Based Student Research Training Program (No. ZN2015080057)

References

[1] Lee S, Park H, Choi K, et al. A Broadband GaN pHEMT Power Amplifier Using Non-Foster Matching. IEEE Transactions on Microwave Theory & Techniques. 63(12) (2015) 4406-4414.

[2] Hörberg M, Emanuelsson T, Lai S, et al. Phase-Noise Analysis of an X-Band Ultra-Low Phase-Noise GaN HEMT Based Cavity Oscillator. IEEE Transactions on Microwave Theory & Techniques. 63(8) (2015) 2619-2629.

[3] Chang T, Hsiao T, Huang C, et al. Phenomenon of drain current instabilityon p-GaN gate AlGaN/GaN HEMTs. IEEE Transactions on Electron Devices. 62(2) (2015) 339-345.

[4] Song B, Sensale-Rodriguez B, Wang R, et al. Effect of Fringing Capacitances on the RF Performance of GaN HEMTs with T-Gates. IEEE Transactions on Electron Devices. 61(3) (2014) 747-754.

[5] Justin B King and Thomas J Brazil, Nonlinear electrothermal GaN HEMT model applied to high-efficiency power amplifier design. IEEE Transactions on Microwave Theory and Techniques. 61(1) (2013) 444-454.

[6] Essaadali R, Jarndal A, Kouki A B, et al. A New GaN HEMT Equivalent Circuit Modeling Technique Based on X-Parameters. IEEE Microwave Theory and Techniques. 64(9) (2016) 2758 - 2777.

[7] Thomas M Antonsen, Alexander N Vlasov, David P Chernin, et al. Transmission line model for folded waveguide circuits. IEEE Transactions on Electron Devices. 60(9) (2013) 2906–2911.

[8] Richard RA Syms, Oleksiy Sydoruk, and Laszlo Solymar. Transmission- line model of noisy electromagnetic media. IEEE Transactions on Microwave Theory and Techniques. 61(1) (2013) 14–22.

[9] Xia K. Modeling the Distributive Effects of RC Transmission Line Using Recursive Segmentation and Applications to MOSFETs and BJTs. IEEE Transactions on Electron Devices. 63(9) (2016) 3385 - 3392.

[10] Curran B, Fotheringham G, Tschoban C, et al. On the Modeling, Characterization, and Analysis of the Current Distribution in PCB Transmission Lines with Surface Finishes. IEEE Transactions on Microwave Theory & Techniques. 64(8) (2016) 2511-2518.

[11] Eisenstadt W R, Eo Y. S-parameter-based IC interconnect transmission line characterization. IEEE Transactions on Components Hybrids & Manufacturing Technology. 15(4) (1992) 483-490

[12] Renu S, Seema V, Rawal D S, et al. RF parameter extraction of MMIC nichrome resistors[J]. Microwave & Optical Technology Letters. 39(39) (2003) 409-412.

[13] Dhaene T, De Zutter D. Selection of lumped element models for coupled lossy transmission lines. IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems. 11(7) (1992) 805-815.