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Small signal modeling of high electron mobility transistors on silicon and silicon carbide substrate with consideration of substrate loss mechanism

A.K. Sahoo [a,*], N.K. Subramani [a], J.C. Nallatamby [a], L. Sylvain [a], C. Loyez [b], R. Quere [a], F. Medjdoub [b]

[a] XLIM Laboratory (XLIM-UMR CNRS 7250), University of Limoges, France
[b] IEMN Laboratory (IEMN-UMR CNRS 8520), University of Lille, France

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ABSTRACT

In this paper, we present a comparative study on small-signal modeling of AlN/GaN/AlGaN double hetero-structure high electron mobility transistors (HEMTs) grown on silicon (Si) and silicon carbide (SiC) substrate. The traditional small signal equivalent circuit model is modified to take into account the transmission loss mechanism of coplanar waveguide (CPW) line which cannot be neglected at high frequencies. CPWs and HEMTs-on-AlN/GaN/AlGaN epitaxial layers are fabricated on both the Si and SiC substrates. *S*-parameter measurements at room temperature are performed over the frequency range from 0.5 GHz to 40 GHz. Transmission loss of CPW lines are modeled with a distributed transmission line (TL) network and an equivalent circuit model is included in the small-signal transistor model topology. Measurements and simulations are compared and found to be in good agreement.

1. Introduction

The development of solid state devices based on conventional semiconductors such as Silicon (Si) and Gallium arsenide (GaAs) for RF and microwave power applications have already approached their physical limits. However, there is an increasing focus on research of III–V nitrides based high electron mobility transistors (HEMT) in the recent years, because of their potential for high power and high temperature applications. This is mainly due to the superior material properties of the gallium nitride (GaN) such as the wide band gap (3.42 eV), high electron mobility (1200 $cm^2/V\,s$), high saturation velocity (2.5×10^7 cm/s), high breakdown electrical field (3.3 MV/cm) and high thermal conductivity (1.3 W/cm K) [1]. Due to the high polarization field properties of the AlGaN and GaN materials, a very high two dimensional electron gas (1×10^{13} cm^{-2}) is formed at the heterojunction interface of the device without the need for any intentional doping [2]. Moreover, the GaN HEMT devices are capable of delivering high output power densities [1] and are considered to be more appealing for the present day communication systems. The commercially available GaN HEMTs are grown on either silicon carbide (SiC) or Si substrates. The GaN HEMTs grown on SiC substrate has already demonstrated the state of art power performance [1,3], owing to their lower substrate loss and high thermal conductivity which allows efficient heat dissipation. Unfortunately, the SiC substrate is extremely expensive and the availability of the large size wafers is limited. It has been reported that the GaN HEMT devices grown on Silicon substrates shows promising performance [4] and it could be an appropriate alternative to SiC substrate due to its low cost with reasonable thermal conductivity [5]. However, the low resistivity of Si substrates induce higher substrate losses [6,7] which hinders the growth of GaN-on-Si HEMT devices for millimeter-wave applications. In recent years, there has been a significant amount of research [8,9] devoted to the development of high resistivity Si substrate for the GaN HEMT devices in order to enable fabrication of high quality microwave circuits. Therefore, it is often emphasised to perform the broadband characterization and modeling of the substrate loss before the integration of these devices into the MMICs.

Despite the fact that GaN HEMT technology has demonstrated its superior performance, the accurate Large Signal Model (LSM) of the transistor is crucial for the successful RF and microwave circuits design. Moreover, the measurements based empirical models are inspired in the recent years and are preferred over the physics based models due to easier CAD implementation of these models [10]. The accurate small signal model (SSM) extraction is a fundamental step in the development of the LSM, the accuracy of the LSM depends mainly on the bias and temperature

* Corresponding author. Tel.: +33 605675070.
E-mail address: amit7phy@gmail.com (A.K. Sahoo).

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dependencies of SSM elements [11]. The most widely used SSM extraction in the past is the numerical optimization of the model parameters to match the model data with the measured *S*-parameters. However, the accuracy of the model parameters depends on the type of optimization method used and also on the initial values assigned to each of the model parameters. Moreover, this technique often results in non-unique values of the model parameters, which has no physical meaning. The direct extraction method is an efficient method to determine the parasitic parameters of the device. Indeed, the extracted parameter values are physically meaningful, while establishing a large signal model. A reliable analytical model for small signal parameters extraction of the traditional GaAs devices was originally proposed by Dambrine [12] and later modified by Berroth and Bosch [13]. However, the method proposed in [12,13] cannot be applied directly to GaN HEMT technology due to their high ohmic contact resistance and gate differential resistance [14]. In the literature, several papers have reported for the SSM extraction of AlGaN/GaN HEMTs. In [14], the authors showed that AlGaN/GaN device exhibits capacitance nature under zero drain-source bias and at large gate bias, because of their higher contact resistances. To model this effect, the capacitance should be included in the transmission-line model. However, the formation of ohmic contacts on AlGaN HEMTs have significantly improved in recent time [9] which offers the lower contact resistances. Chigaeva et al. [15] showed that the elements of the SSM can be extracted from cold FET *S*-parameter measurements at a high gate-forward voltage, which suppresses the differential gate resistance. However, this method requires a very high positive bias applied at the gate, which can damage the Schottky diode gate of AlGaN HEMT. In [15], a reliable low gate bias model extraction method has been proposed and demonstrated an efficient SSM parameters extraction.

In this paper, we first characterize the broadband frequency performance of CPWs built on AlN/GaN/AlGaN HEMT layers grown on Si and SiC substrates. Transmission loss of CPWs are modeled using *n*-cells distributed transmission line model and an equivalent type circuit model is included in the traditional small signal model. The small-signal measurements and modeling are performed for AlN/GaN/AlGaN HEMT grown on Si and SiC substrates with the following device dimensions: gate length (L_G) = 0.12 μm, gate-drain distance (L_{GD}) = 2.0 μm and gate width (W_G) = 2 × 100 μm respectively. The small signal parameters extraction method proposed in [15] is used for the model extraction. Section II describes the small signal measurements and modeling of CPWs and HEMTs grown on Si and SiC substrates with consideration of substrate loss effects and Section III concludes the paper.

2. Small-signal measurements and modeling of CPWs and HEMTs

The AlN/GaN/AlGaN double heterostructures were grown by metal–organic chemical vapor deposition (MOCVD) on a 550-μm SiC substrate and HR–Si (1 1 1) (ρ > 5000 Ω cm) substrate. The epilayers consist of a 1.5 μm thick $Al_{0.08}Ga_{0.92}N$ buffer layer, 150 nm thick GaN channel layer followed by a 6 nm ultrathin AlN barrier layer and 3 nm in-situ grown Si_3N_4 cap layer. Ni/Au Schottky gate contact and Ti/Al/Mo/Au metal stack for ohmic source and drain

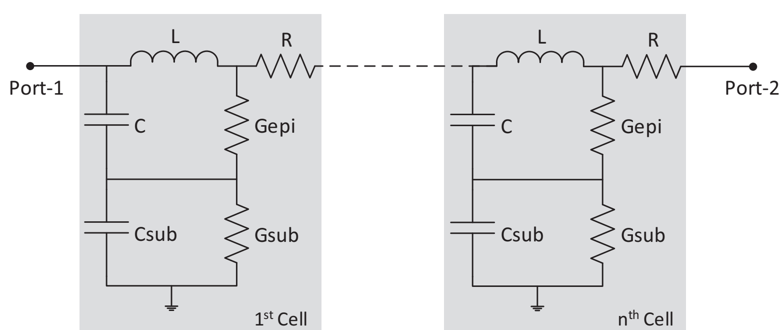

Fig. 1. *n*-Cells distributed model of CPW including substrate loss.

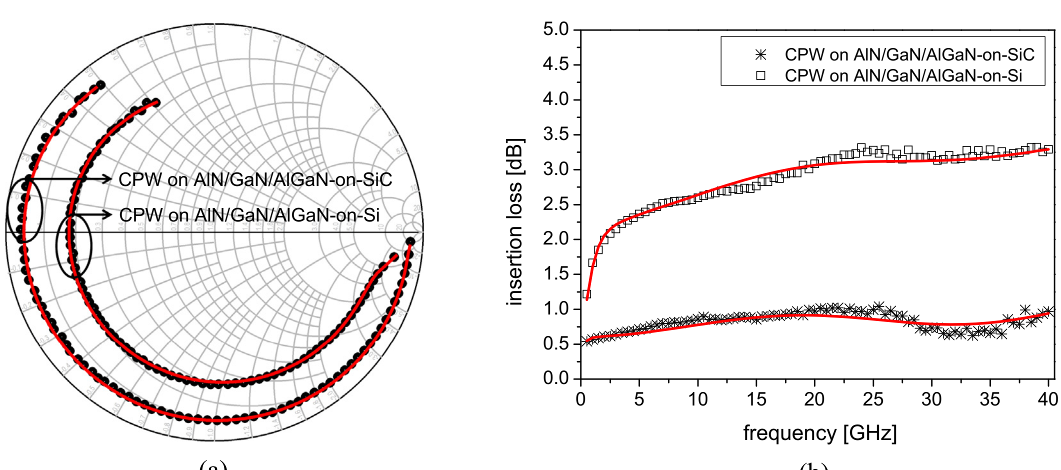

Fig. 2. (a) Transmission coefficient, S_{21}, in Smith chart, and (b) insertion loss of CPW on AlN/GaN/AlGaN-on-Si and SiC: comparison between measurements (symbols) and model (lines).