Short Papers

Simulation of HEMT DC Drain Current and 1 to 50 GHz S-Parameters as a Function of Gate Bias

Simon J. Mahon, Michael J. Chivers, and David J. Skellern

Abstract—**The usefulness over an extended range of a HEMT model previously validated for 1 to 25 GHz s-parameter model is shown. Experimental and simulation results for the dc drain current and 1–50 GHz *s*-parameters of a pseudomorphic 0.32-μm-gate AlGaAs/InGaAs/GaAs HEMT are presented. The model predicts the device's dc current and *s*-parameters as a function of the applied gate bias with good accuracy. The core of the model is directly dependent on the HEMT wafer structure and the physical gate length. As part of the modeling procedure, a value of $(1.77 \pm 0.07) \times 10^5$ m · s^{-1} is found, confirming the results of other research, for the electron velocity in undoped pseudomorphic $In_{0.15}Ga_{0.85}As$ under $\approx$ 0.3μm gates.**

I. Introduction

In a previous paper [1], we presented a semi-physical HEMT model which produced a good fit to measured *s* -parameter data as a function of the applied gate bias for frequencies between 1 and 25 GHz. In this paper we establish the wider usefulness of the model by comparison of experimental and simulation results for dc drain current and 1 to 50 GHz *s*-parameters as a function of the applied gate voltage. We also provide a confirmation of a previously published value of electron velocity in undoped pseudomorphic $In_{0.15}Ga_{0.85}As$ and doped $Al_{0.25}Ga_{0.75}As$. The HEMT model uses an equivalent of circuit constructed from lumped elements as shown in Fig. 1. The composition of the HEMT wafer is used in the model to determine the gate bias dependence of the transconductance (gm), output conductance (gds), gate-source capacitance (Cgs) and gate-drain capacitance (Cgd). In our model, the bias dependence of the device's *s*-parameters is solely due to the bias dependence of these four elements.

II. Experimental Details

The modeled device, PH109-12H, was fabricated by the CSIRO Division of Radiophysics on their wafer constructed as follows. An AlGaAs/GaAs superlattice was grown on a semiinsulating GaAs substrate ($\approx 600\mu$m thick) using molecular beam epitaxy. On top of this a 135-nm-thick layer of undoped GaAs was grown, followed by a 15-nm-thick layer of undoped pseudomorphic $In_{0.15}Ga_{0.85}As$, and a 53.5-nm-thick layer of doped $Al_{0.25}Ga_{0.75}As$. The silicon dopant density was $(7.8 \pm 0.2) \times 10^{23}\mathrm{m}^{-3}$. The estimated error in the layer thicknesses is ± 1 nm.

To produce good quality ohmic contacts, a 75-nm-thick GaAs capping layer, doped to a density of approximately $8 \times 10^{24}\mathrm{m}^{-3}$, was grown on top of the AlGaAs layer. The ohmic contacts were made with a gold–germanium–nickel alloy. The 0.32-μm-long $\times 125$-μm-wide gold–palladium gate was released using direct-write electron beam lithography and dry-etch process to remove the GaAs capping layer.

These average values are obtained from destructive tests on similar devices [2, Fig. 3]. The InGaAs layer thickness, In fraction, AlGaAs layer thickness, Al fraction, Si doping density in the AlGaAs, gate length, and gate widths are inputs to the HEMT model's calculation gm, gds, Cgs and Cgd at each bias point.

The HEMT was probed using a Cascade Summit 1000 Semiautomatic Probe Station. A Hewlett-Packard 8510C was used to measure the device's *s* -parameters from 1 to 50 GHz. The dc and *s*-parameter measurements were taken with the drain-source voltage set to 2 V and the gate-source voltage varying from −0.6 V to 0.0 V in 0.2-V steps.

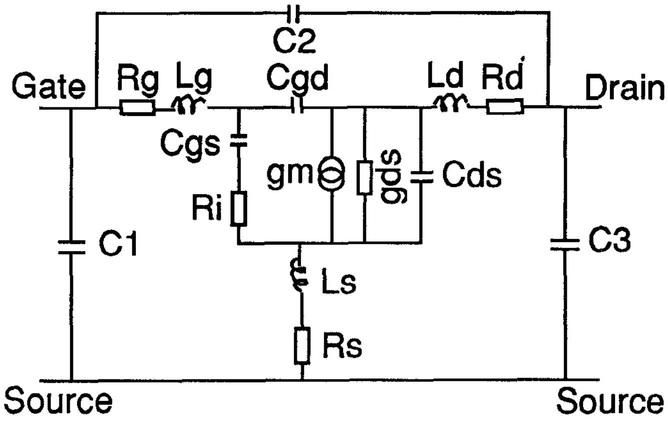

Fig. 1. HEMT equivalent circuit. $C1$, $C2$, and $C3$ are pad-to-pad capacitances.

III. Results and Discussion

The fit to the measured data was obtained by defining an error metric between the measured and modeled data. The total error E is defined as

$$E = W_{Ids} \cdot E_{Ids} + W_{s11} \cdot E_{s11} + W_{s12} \cdot E_{s12} + W_{s21} \cdot E_{s21} + W_{s22} \cdot E_{s22} \quad (1)$$

where $W_{Ids}, W_{s11}, W_{s12}, W_{s21}$, and W_{s22} are the weights placed on the relative rms errors, E_{Ids}, $E_{s11}, E_{s12}, E_{s21}$, and E_{s22}. The error E_{Ids} is defined as

$$E_{Ids} = \frac{\sum |Ids_{(\text{measured})} - Ids_{(\text{model})}|^2}{\sum |Ids_{(\text{measured})}|^2} \quad (2a)$$

where the summations are over all bias points. The *s*-parameter errors, $E_{ij}(i, \ j = 1, 2)$, are defined as

$$E_{ij} = \frac{\sum |s_{ij(\text{measured})} - s_{ij(\text{model})}|^2}{\sum |s_{ij(\text{measured})}|^2} \quad (2b)$$

where the summations are over all frequencies and all bias points.

The value of E was minimized using a complex search algorithm [2] to choose the optimal values of the empirical parameters (listed in Tables I and II). These are combined with the known

Manuscript received April 6, 1992; revised October 13, 1992. The work was supported by the CSIRO Division of Radiophysics.

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IEEE Log Number 9208368.

TABLE I
VALUES OF THE SATURATION VELOCITY, CRITICAL ELECTRIC FIELD AND LOW-FIELD MOBILITY FOR THE TWO DIMENSIONAL ELECTRON GAS (2DEG) AND PARASITIC MESFET (PM) CONDUCTION PATHS IN THE HEMT.

Paramater	2DEG	PM	Unit
Saturation velocity	1.77	0.86	x 10^5 m.s^{-1}
Critical electric field	1.1	0.66	x 10^6 V.m^{-1}
Low-field mobility	0.97	0.44	m^2.V^{-1}.s^{-1}
Channel length modulation	0.026	0.042	V^{-1}
Drain feedback factor	0.11	0.20	–

TABLE II
VALUES OF ADDITIONAL PARAMETERS USED BY THE HEMT MODEL TO CALCULATE THE VALUES OF *gm, gds, Cgs,* AND *Cgd.*

Parameter	Value	Unit
Device temperature	347	K
Electron transit time	2.2	ps
Gate-source peripheral capacitance (Cgsp)	63	fF
Gate-drain peripheral capacitance (Cgdp)	3.8	fF
Voltage dependence of Cgsp	1.7	V^{-1}
Voltage dependence of Cgdp	-0.24	V^{-1}

TABLE III
VALUES OF THE ELEMENTS *C1, C2, C3, Ld, Ls, Lg, Rd, Rs, Rg, Ri, Cds* IN THE EQUIVALENT CIRCUIT MODEL SHOWN IN FIG. 1.

	Value	Unit		Value	Unit		Value	Unit
Rg	5.4	Ω	Rs	2.9	Ω	Rd	2.8	Ω
Lg	32	pH	Ls	0.12	pH	Ld	47	pH
C1	30	fF	C2	24	fF	C3	9.9	fF
Ri	9.5	Ω	Cds	12	fF			

TABLE IV
RELATIVE RMS ERROR BETWEEN THE MEASURED AND MODELED DC DRAIN CURRENT AND 1 TO 50 GHz *S*-PARAMETERS FOR THE FOUR BIASES (THE WEIGHTED TOTAL ERROR AND THE INDIVIDUAL WEIGHTS ARE ALSO LISTED).

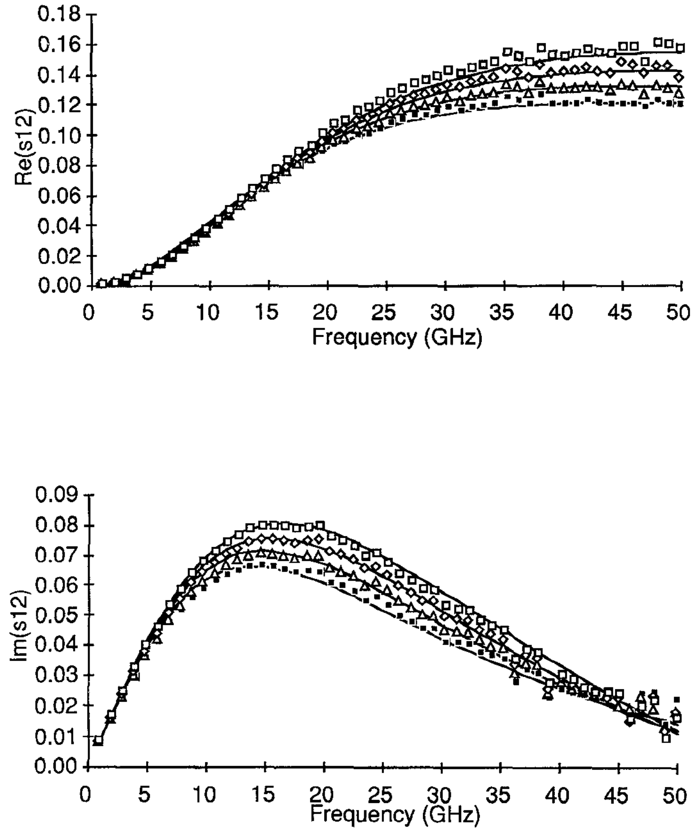
	Weighting	Error (%)
Ids	0.05	6.23
s_{11}	0.15	3.72
s_{12}	0.10	3.57
s_{21}	0.55	4.35
s_{22}	0.15	2.65
Total	1.00	4.01

TABLE V
MEASURED AND MODELED VALUES OF DC DRAIN CURRENT (Ids) AND A FUNCTION OF GATE-SOURCE VOLTAGE (Vgs).

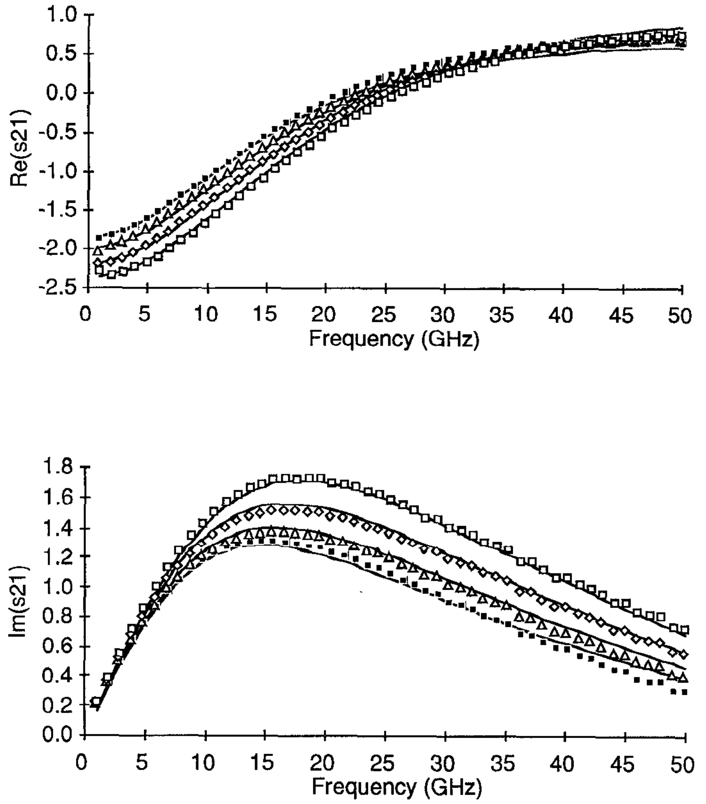
Vgs	Measured Ids	Simulated Ids
-0.6 V	18.5 mA	19.5 mA
-0.4 V	25.2 mA	24.8 mA
-0.2 V	31.5 mA	29.6 mA
0.0 V	36.9 mA	34.0 mA

wafer structure (described in Section II) to calculate the values of gm, gds, Cgs, and Cgd at each bias point. The complex search algorithm is also used to choose the optimal (fixed) values for $C1$, $C2$, $C3$, Ld, Ls, Lg, Rd, Rs, Rg, Rin, and Cds (Table III).

Table IV lists the weights used in modeling the HEMT and the resulting errors. Table V lists the measured and simulated values of Ids. Figure 2 shows the agreement between the measured s_{12} and s_{21}-parameter data and the model predictions for this device. The model produces a good fit to the dc Ids data and 1 to 50 GHz s-parameter data as a function of the gate-source bias.



(a)



(b)

Fig. 2. The real and imaginary part of the measured (symbols) and simulated (solid lines) s_{12} and s_{21}-parameters. The biases are $Vgs = -0.6$ V (□), -0.4 V (◇), -0.2 V (△), and 0.0 V (■).

The optimization algorithm determined the saturated electron velocity in the two-dimensional electron gas to be $(1.77 \pm 0.07) \times 10^5 \mathrm{m} \cdot \mathrm{s}^{-1}$. This value is in good agreement with the value of $1.8 \times 10^5 \mathrm{m} \cdot \mathrm{s}^{-1}$ reported by de la Houssaye *et al.* [3] for a pseudomorphic AlGaAs/InGaAs HEMT with a 0.3-μm-long gate and a 15% indium fraction. The error in the 2DEG velocity is estimated by repeating the optimization with the critical parameters of doping density and doped layer thickness set to their worst case values, $(8.0 \times 10^{23} \mathrm{m}^{-3}, 54.5$ nm) and $(7.6 \times 10^{23} \mathrm{m}^{-3}, 52.5$ nm), and the other parameters held constant at the values listed in Section II and Tables I–III.

The optimization algorithm also determined the saturated electron velocity in the parasitic MESFET to be $8.6 \times 10^4 \mathrm{m} \cdot \mathrm{s}^{-1}$. This value is in good agreement with the value of $8.9 \times 10^4 \mathrm{m} \cdot \mathrm{s}^{-1}$ reported in [2] for a standard AlGaAs/GaAs HEMT with a 25% aluminum fraction and a 0.25-μ m-long gate.

IV. Conclusion

In this paper we have established the usefulness over an extended range of a previously reported model [1]. Good agreement has been obtained between measured and simulated dc drain current and s-parameters from 1 to 50 GHz, both as a function of the applied gate voltage. We have also confirmed a published value of $\approx 1.8 \times 10^5 \mathrm{m} \cdot \mathrm{s}^{-1}$ for the saturated electron velocity in the pseudomorphic $\mathrm{In_{0.15}Ga_{0.85}As}$ channel layer of a HEMT with a gate length of ≈ 0.3 μm, and obtained again from unrelated measurements a saturated electron velocity of $\approx 8.9 \times 10^4 \mathrm{m} \cdot \mathrm{s}^{-1}$ in the doped $\mathrm{Al_{0.25}Ga_{0.75}As}$ layer of a HEMT with a gate length ≈ 0.25 μm.

Acknowledgment

We thank T. Fiocco for measuring the s-parameter data, and F. Green, N. Barrett, G. Griffiths, W. King, R. Batchelor, and J. W. Archer from the CSIRO Division of Radiophysics for structural measurements and many useful discussions. M. J. Chivers also acknowledges the support of an ATERB scholarship.

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Millimeter-Wave Three-Port Finline Circulator Using Distributed Coupling Effect

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Abstract—**The design and experimental results for a novel three-port finline circulator are presented for the frequency range 26–40GHz. The circulator consists of a T^E-junction cascaded with the section of ferrite coupled slot finlines magnetized in the propagation direction. The T^E-junction structure refers to a transition from unilateral single slot finline taper into coplanar line region via a tapered center conductor. The design procedure of the structure confirmed by experimental results is described. The proposed structure adjoins to the family of the distributed coupled ferrite line nonreciprocal devices suitable for application in the millimeter-wave range.**

I. Introduction

Recently, a number of novel nonreciprocal components applicable at millimeter-wave frequencies has been presented [1], [2]. The principle of operation of some of these devices was based on the nonreciprocal Faraday rotation phenomenon appearing in distributed coupled ferrite line structures magnetized longitudinally in the propagation direction [3], [4]. The mathematical model of the phenomena proposed in [3] and [4] makes it possible to predict the nonreciprocal behavior of the section of coupled ferrite lines, and provides conditions indispensable to design the structure. In this paper, a new three-port finline circulator based on the concept proposed in [4] is presented. The circuit employs a combination of unilateral finline T^E-junction and a section of coupled ferrite slot finline. The nonreciprocity conditions formulated in [4] were used to design the structure of the device. Nonreciprocal operation of the proposed circuit, confirmed by experimental results, indicates the validity of the theory and of the design procedure.

II. Nonreciprocity Condition

Before presentation of the design of a three-port circulator, it will be useful to recall some points of the theory presented in [3] and [4]. Using the coupled mode method, the scattering matrix of coupled ferrite lines (CFL) magnetized in the propagation direction has been reported in [4]. Under the assumption that reflected waves are neglected in the structure, the scattering matrix of CFL is given by

$$\underline{\underline{S}}^f = \begin{bmatrix} 0 & 0 & s_1 & -s_2^* \\ 0 & 0 & s_2 & s_1 \\ s_1 & -s_2^* & 0 & 0 \\ s_2 & s_1 & 0 & 0 \end{bmatrix} e^{j\beta_0 z} \tag{1}$$

with

$$s_1 = \cos(\Gamma z) \qquad s_2 = \frac{\pm|C| - j\Delta\beta}{\Gamma} \sin(\Gamma z) \tag{2}$$

and

$$\beta_o = \frac{\beta^e + \beta^o}{2} \qquad \Gamma = \sqrt{\Delta\beta^2 + C^2} \qquad \Delta\beta = \frac{\beta^e - \beta^o}{2}.$$

Manuscript received April 6, 1992; revised October 15, 1992. This work was supported in part by the Committee of Sciences via the Technical University of Gdansk under Contract 916316.

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IEEE Log Number 9208351.