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# High Frequency Analysis and Small-Signal Modeling of AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs with SiO<sub>2</sub>/Si<sub>3</sub>N<sub>4</sub> Passivation

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## Abstract

AlGa<sub>N</sub>/Ga<sub>N</sub> high electron mobility transistors (HEMTs) on Silicon substrates grown by molecular beam epitaxy have been investigated using small-signal microwave measurements, to see performance Radio-frequency of components. Passivation of HEMT devices SiO<sub>2</sub>/Si<sub>3</sub>N<sub>4</sub> a different pretreatment is used to reduce the effects of trapping and consequently has a large effect on these radio-frequency parameters. We used cold-FET and hot FET technique to extract the intrinsic and extrinsic parameters in order to show the effect passivation of parasitic elements; the parasitic capacitances, resistances and inductances. From this point we discover the extent of their impact on power and microwave performance.

**Keywords** AlGa<sub>N</sub>/Ga<sub>N</sub>/Si HEMTs · Passivation · Radio-frequency · Equivalent circuit parameters · Small signal modeling

## 1 Introduction

AlGa<sub>N</sub>/Ga<sub>N</sub> based high electron mobility transistors are excellent candidates for high frequency and high power applications [1–3]. The primary reason in the nitride gallium- based materials have wide band gaps, an efficient carrier transport, large breakdown bias voltages and strong spontaneous and piezoelectric polarization fields [4]. The direct-current and radio-frequency parameters are found to improve after passivation [5]. Modeling of AlGa<sub>N</sub>/Ga<sub>N</sub>/Si HEMTs for the subsequent design a low-noise amplifier is the objective of our study.

## 2 AlGa<sub>N</sub>/Ga<sub>N</sub>/Si HEMT Structure

The AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs under investigation are grown on silicon (111) substrate by using molecular beam epitaxy (MBE) (present some high purity). The active layers consist in a 500 nm thick of undoped AlN/AlGa<sub>N</sub> buffer, a 1.8 μm undoped Ga<sub>N</sub> channel, a 23 nm thick of undoped Al<sub>0.26</sub>Ga<sub>0.74</sub>N barrier and a 1 nm n<sup>+</sup>-Ga<sub>N</sub> cap layer. The device processing is made following conventional HEMT fabrication steps. The ohmic contact pads are patterned using e-beam lithography. Hereafter, the metallization by means of evaporated 12/200/40/100 nm Ti/Al/Ni/Au is deposited at 900 °C during 30 s. The Schottky gate is realized using 100/150 nm Mo/Au layers. On the other hand, the AlGa<sub>N</sub>/Ga<sub>N</sub> HEMTs are passivated by 100/50 nm SiO<sub>2</sub>/Si<sub>3</sub>N<sub>4</sub> with pretreatment N<sub>2</sub>O and NH<sub>3</sub>.

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## 3 Experimental Result

S-parameters measurement is an important step for estimating RF-performance of power component, and to extract the various parameters of linear model. Measurements of these parameters were performed under coplanar points up to 60 GHz using a vector network analyzer to characterize sam-

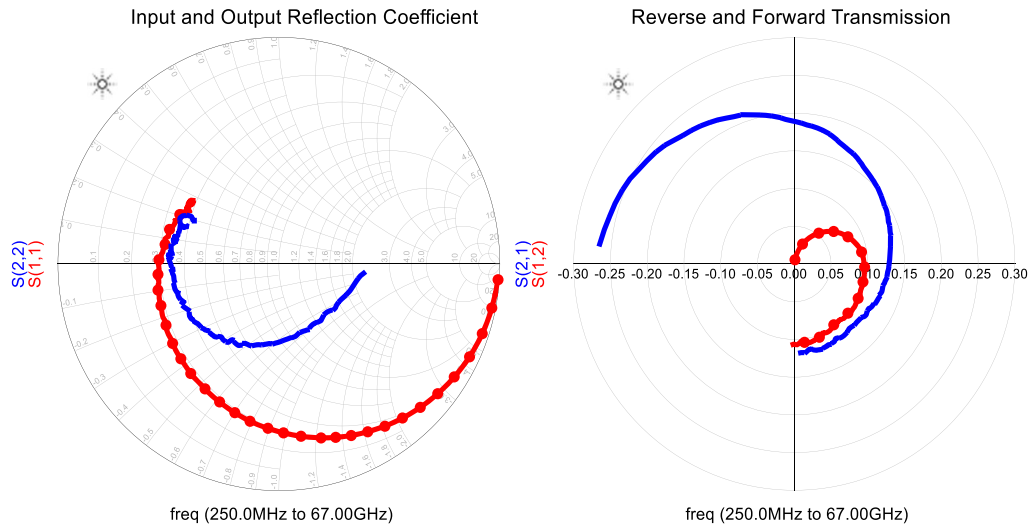


Fig. 1 Measured S-parameters before passivation of AlGaIn/GaN/Si HEMT

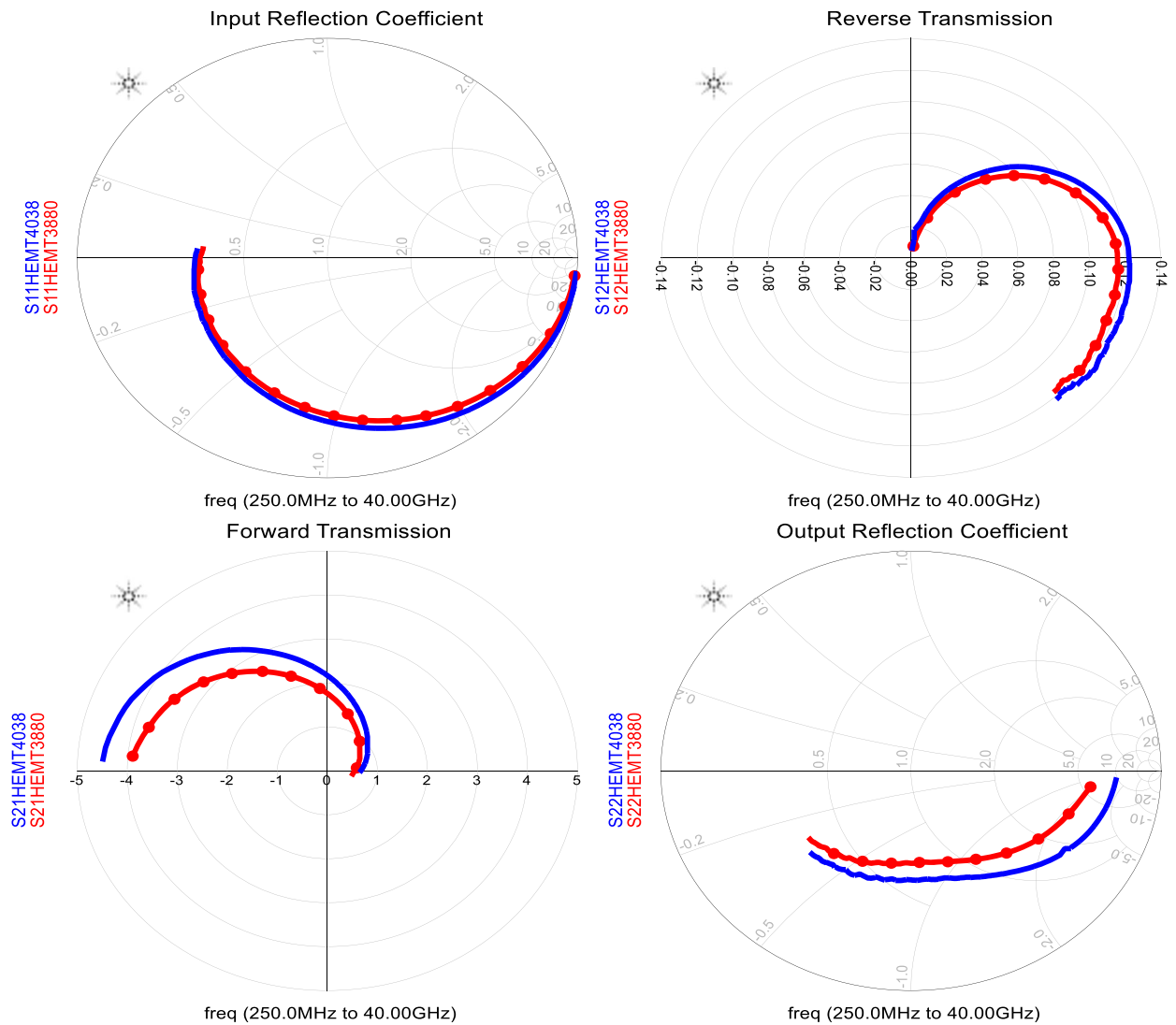
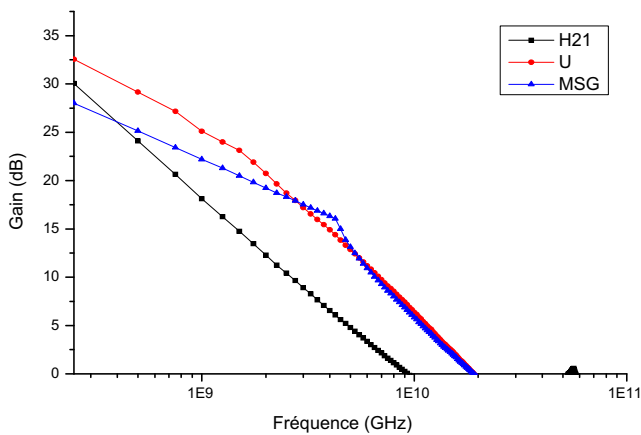


Fig. 2 Measured S-parameters after passivation and with pretreatment of AlGaIn/GaN/Si HEMT



**Fig. 3** Measured current gain ( $H_{21}$ ), unilateral power gain (U) and maximum available gain (MSG) before passivation of AlGaIn/GaN/Si HEMT

ples passivated  $\text{SiO}_2/\text{SiN}$  with  $\text{N}_2\text{O}$  and  $\text{NH}_3$  pretreatment respectively.

Figure 1 shows the experimental S-parameters of AlGaIn/GaN/Si HEMT before passivation on a frequency range extends from 250 MHz to 67 GHz in 0.25 GHz step. for a bias  $V_{gs} = -1, 25$  V and  $V_{ds} = 15$  V.

Figure 2 shows the measured scattering parameters of samples after passivation, we observe that the S-parameters spread more than before passivation Fig. 1; this change has a great influence on the performance frequency.

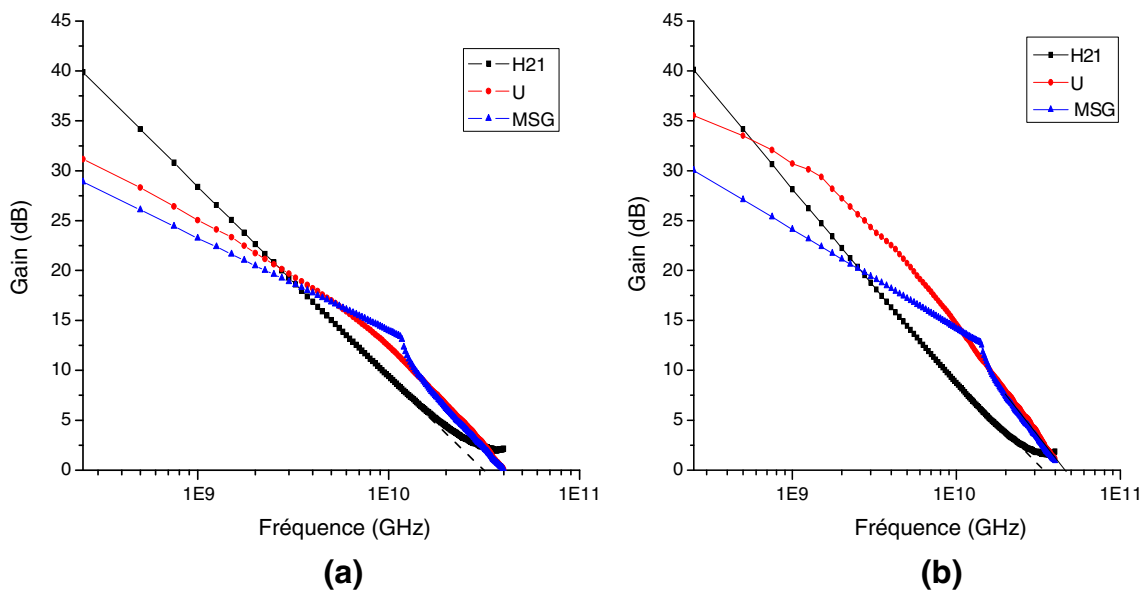
**Table 1** Frequency characteristics

Sample	$F_T$ (GHz)	$F_{max}$ (GHz)	$F_{MSG}$ (GHz)
Unpassivated	9,6	18,5	18,4
Passivated $\text{SiO}_2/\text{SiN}$ with $\text{NH}_3$ pretreatment	32,2	41,9	41,9
Passivated $\text{SiO}_2/\text{SiN}$ with $\text{N}_2\text{O}$ pretreatment	34,8	47,9	47,9

From on wafer S-parameters measurements, Standard extrapolations of frequency dependences of current gain ( $|H_{21}|$ ), the Mason gain (U) and maximum available gain (MSG) to higher frequencies in the shape of straight lines with the slope of  $-20\text{dB/decade}$  were used to determine their points of intersection with the frequency axis. We have deduced the frequency parameters a function of frequency ranging from 250 MHz to 60 GHz.

Figures 3 and 4 shows the gains before and after passivation for different pretreatment. The current gain and the maximum available gain to determine limits frequency of the microwave component; cut-off and maximum frequency respectively. Table 1 summarizes the main characteristics microwave.

We see from this table that passivation and surface treatment improves the performance of different frequencies. The sample passivated  $\text{SiO}_2/\text{SiN}$  with  $\text{N}_2\text{O}$  pretreatment corresponding largest frequencies; this can be explained by



**Fig. 4** Measured current gain ( $H_{21}$ ), unilateral gain (U) and maximum available gain (MSG) after passivation of AlGaIn/GaN/Si HEMT: (a), (b)

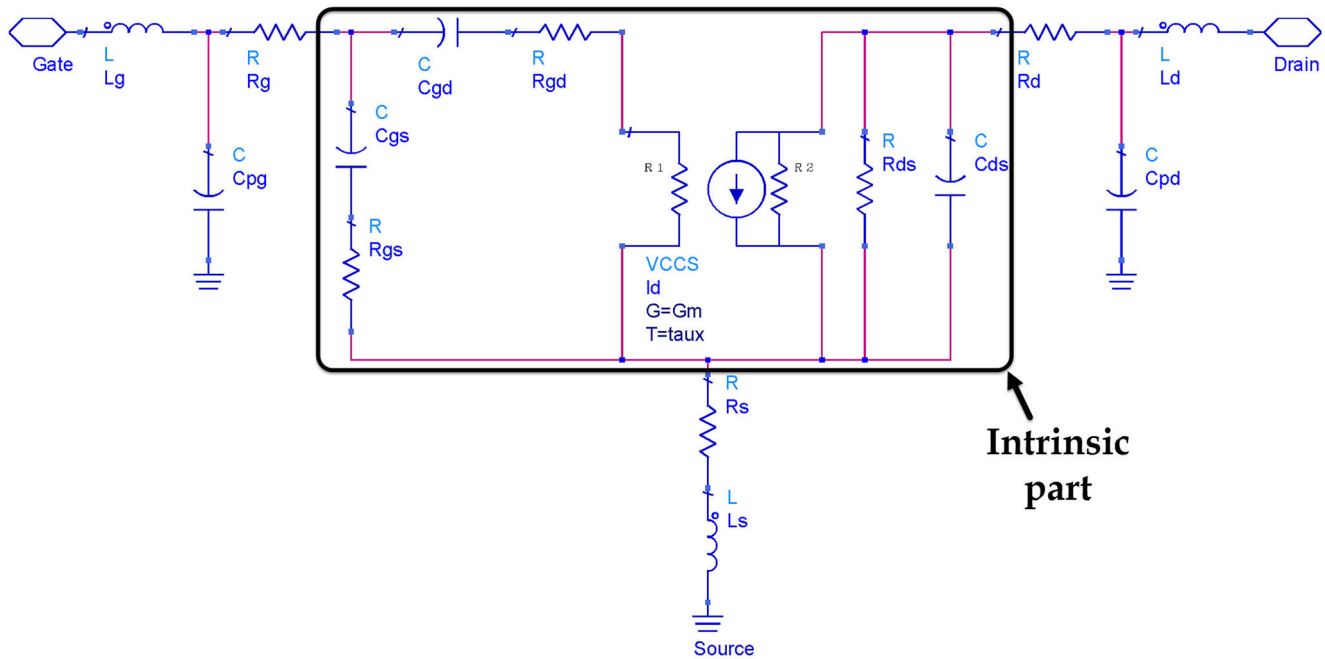


Fig. 5 Small-signal equivalent circuit of a transistor HEMTs

the larger current as well as the higher speed of the carriers in this structure [6]. Indeed, as the structure is undoped, investors are best confined to the interface AlGa<sub>N</sub>/Ga<sub>N</sub> and do not enter a low mobility layer.

The extrinsic values  $F_t$  and  $F_{max}$  increase respectively from 9.6 GHz to 32.2 GHz for NH<sub>3</sub> pretreatment and 34.8 GHz for N<sub>2</sub>O pretreatment and 18.5 GHz to 41.9 GHz for NH<sub>3</sub> and 47.9 GHz for N<sub>2</sub>O pretreatment. Also, after passivation the  $F_{max}/F_T$  ratio is close to 1, it attests a good confinement of the charges in the channel and confirms the absence of charge coupling effects with the substrate as observed on conductive substrates [7].

#### 4 Small-Signal Modeling of AlGa<sub>N</sub>/Ga<sub>N</sub>/Si HEMT

The equivalent circuit model used for microwave HEMTs is presented in Fig. 5 [8]. It contains two parts; an intrinsic part corresponds to the active portion of the transistor and an extrinsic part outside the active region, which includes the RF contact pads and gate, drain, and source metallization.

The extraction method used is based on measurements of the small signal S-parameters, the most commonly used technique, it uses two measures S-parameters for different measuring polarization conditions; measuring cold FET and measure hot FET [9, 10].

The extrinsic equivalent circuit parameters can be evaluated from S-parameters measurements under cold and pinched conditions;  $V_{ds} = 0$  V and  $V_{gs} \ll V_p$ ,  $V_p$  is the

plucking voltage when the conduction transistor channel [10, 11]. The most common method can be categorized into analytical and optimization based.

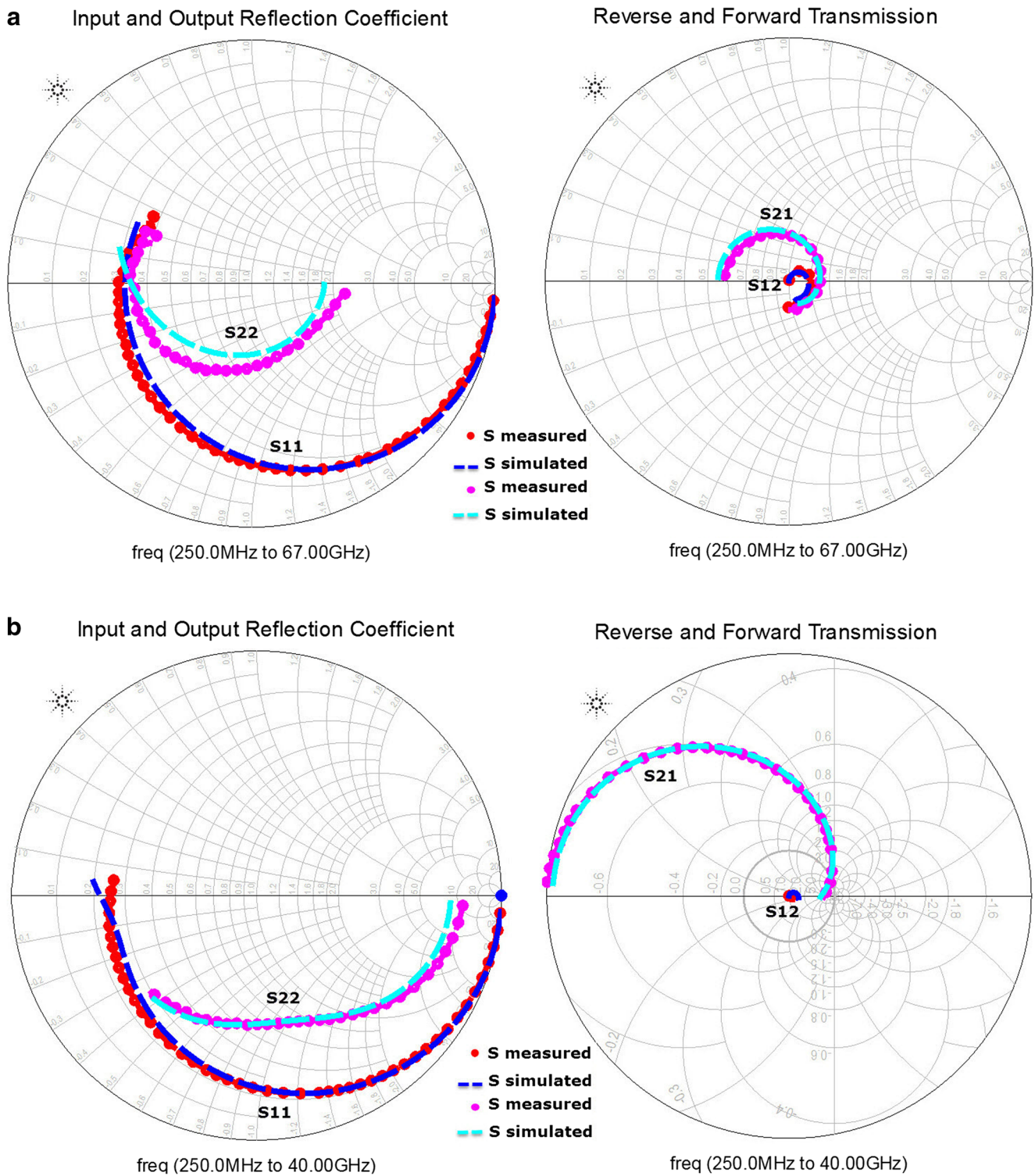
For a game of extrinsic parameters given, one can determine the intrinsic elements from a series of matrix manipulation, comparable to a peeling process of the outer layers to reach the heart of the component [12–14].

The comparison of the measured data (circles) with simulation results (lines) for the S-parameters variation of the model before and after passivation is shown in Fig. 6. The agreements between the measured and modeled data are excellent in a wide frequency range. The extracted values for all extrinsic and intrinsic parameters are listed in Table 2.

One of the main factors affecting the gain of a FET is the feedback capacitance  $C_{gd}$ . Usually, the gate-drain capacitance is almost independent of the gate voltage it decreases with increasing drain voltage. This shows the advantage of biasing the device at larger drain voltages for better gain. Therefore, these devices have improved MSG (Maximum Stable Gain) with increasing drain bias voltage due to reduced feedback capacitance [15].

In this context, we see that this capacity decreases to 271.1 pF before passivation to reach 114.2 pF and 126.8 pF after passivation with N<sub>2</sub>O and NH<sub>3</sub> pretreatment respectively. From this point, we deduce that components with O<sub>2</sub>N pretreatment may give more power.

We observe that the gate-resistance is reduced to 7.5  $\Omega$  before passivation to up nearly half after passivation with N<sub>2</sub>O pretreatment, this has led to improve the output



**Fig. 6** Measured (mes) and modeled (mod) S-parameters of HEMT: A—before passivation, B—after passivation

performance of AlGaIn/GaN/Si HEMT devices. Because, increasing gate resistance implies increasing the charging delay time and this results in decreasing the speed of device [16].

The RF parameters of AlGaIn/GaN/Si HEMTs are improving more after passivation by SiO<sub>2</sub>/SiN with N<sub>2</sub>O pretreatment. Then, choose this passivation with this treatment during elaboration for this type device.



**Table 2** Extracted parameters values before and after passivation a different pretreatment

Sample		Unpassivated	Passivated SiO <sub>2</sub> /SiN with NH <sub>3</sub> pretreatment	Passivated SiO <sub>2</sub> /SiN with N <sub>2</sub> O pretreatment
Extrinsic parameters	L <sub>g</sub> (pH)	44.7	37.1	36.2
	L <sub>s</sub> (pH)	10.2	6.7	5.5
	L <sub>d</sub> (pH)	92.2	27.3	59.8
	R <sub>g</sub> (Ω)	7.5	4.3	3.8
	R <sub>s</sub> (Ω)	8	3	1.5
	R <sub>d</sub> (Ω)	72.2	20.4	13.7
	C <sub>pg</sub> (fF)	30	21.5	19.6
	C <sub>pd</sub> (fF)	62.7	38.5	32.5
Intrinsic parameters	C <sub>gs</sub> (fF)	351.4	420.5	429.3
	C <sub>gd</sub> (fF)	271.1	126.8	114.2
	C <sub>ds</sub> (fF)	194.5	103.5	93.1
	R <sub>gs</sub> (Ω)	3.25	5.2	4.5
	R <sub>gd</sub> (Ω)	9.6	4.5	3.2
	R <sub>ds</sub> (Ω)	8.8	266	318
	G <sub>m</sub> (mS)	47	64	66.5
	τ (ps)	1.32	0.33	0.21

## 5 Conclusion

We have presented in this work the effect of SiO<sub>2</sub>/SiN passivation with different pretreatment on power and microwave performance, SiO<sub>2</sub>/SiN is shown to be of high quality and stoichiometric in composition. It reduces the relaxation, cracking, and surface roughness of the AlGa<sub>0.3</sub>N layer. As has been shown that as the passivation with N<sub>2</sub>O pretreatment gives better results, it makes the device more quickly and give more power. This leads to devices with greatly improved characteristics.

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