MEXTRAM model based SiGe HBT large-signal modeling*

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Abstract: An improved large-signal equivalent-circuit model for SiGe HBTs based on the MEXTRAM model (level 504.5) is proposed. The proposed model takes into account the soft knee effect. The model keeps the main features of the MEXTRAM model even though some simplifications have been made in the equivalent circuit topology. This model is validated in DC and AC analyses for SiGe HBTs fabricated with 0.35-μm BiCMOS technology, 1×8 μm^2 emitter area. Good agreement is achieved between the measured and modeled results for DC and S-parameters (from 50 MHz to 20 GHz), which shows that the proposed model is accurate and reliable. The model has been implemented in Verilog-A using the ADS circuit simulator.

Key words: heterojunction bipolar transistor; large-signal model; Verilog-A; soft knee effect; MEXTRAM model

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1. Introduction

Nowadays, the rapid growth in wireless communication at radio frequencies has created a huge demand in high-performance RF components for power amplifiers in base stations and automotive applications. Due to a higher integration level than III–V devices, SiGe HBTs quickly become popular in wireless communication applications, in the form of wireless transceiver circuits. Optimal designs for RF power amplifiers and IC-applications require accurate models, especially physical-oriented models, for circuit simulation, which is valid in DC and AC conditions over a wide range of frequency and bias.

Conventional bipolar junction transistor models, such as the more than 30-year-old SPICE Gummel–Poon model (SGPM)[1], are used for the design of analog high-frequency circuits fabricated in advanced Si/SiGe bipolar and BiCMOS, as well as in III–V HBT technologies. The formulation of charges storage effects as well as the missing self-heating and base-collector avalanche effect are the most important deficiencies of the conventional models. Some advanced compact models, such as VBIC[2], HICUM[3] and MEXTRAM[4] models, which were initially developed for silicon and SiGe devices, have eliminated many of the above issues. The VBIC model includes improved modeling of the early effect, quasi-saturation, substrate and oxide parasitics, avalanche multiplication, and temperature behavior. The HICUM (high-current model) model was developed for high-current and high-speed digital applications. This model is a physics-based model and has a completely different transit time approach compared with the SGP and MEXTRAM models. The MEXTRAM 504 model has an improved cut-off frequency model as using a different principle than HICUM for transit time modeling. However, the VBIC, HICUM and MEXTRAM models are more complicated than the SGP model with respect to model equations, equivalent-circuit and computational effort, and the convergency behavior of the VBIC, HICUM and MEXTRAM models are not as good as the SGP model. Other compact models, such as the Agilent HBT[5] and FBH HBT[6] models, were created specifically for III–V material devices.

The availability of a simplified model may have certain advantages[7], thus a less complicated compact heterojunction bipolar transistor model has been developed on the basis of the MEXTRAM 504.5 model. Compared to the MEXTRAM model, the soft knee effect has been taken into account, and the parameter extraction effects, especially for single transistor sizes, becomes convenient. The proposed model accurately describes the electrical behavior of SiGe HBTs fabricated with 0.35-μm BiCMOS technology from DC to 20 GHz over the entire range of bias conditions.

2. Model description

Figure 1 shows the proposed large-signal equivalent circuit model. This consists of a fundamental transistor part as well as a sub-circuit to model self heating.

Compared to the MEXTRAM 504.5 model, the following modifications have been made:

(1) The sidewall components $I_{\rm B1}^{\rm S}$ and $Q_{\rm tE}^{\rm S}$ have been eliminated by properly merging the bulk and the sidewall component across the BE junction, then the separation parameters $XI_{\rm B1}$ and $XC_{\rm JE}$ are not included in the proposed model. The ideal forward base current can be written as follows:

$$I_{\rm B1} = \frac{I_{\rm ST}}{q_{\rm k}\beta_{\rm fT}}({\rm e}^{v_{\rm B2E1}/V_{\rm T}} - 1). \quad (1)$$

In the above equation, $q_{\rm k}$ will be discussed later in more detail. The total base–emitter depletion capacitance can be written as follows:

$$Q_{\rm tE} = C_{\rm jET}V_{\rm tE}. \quad (2)$$

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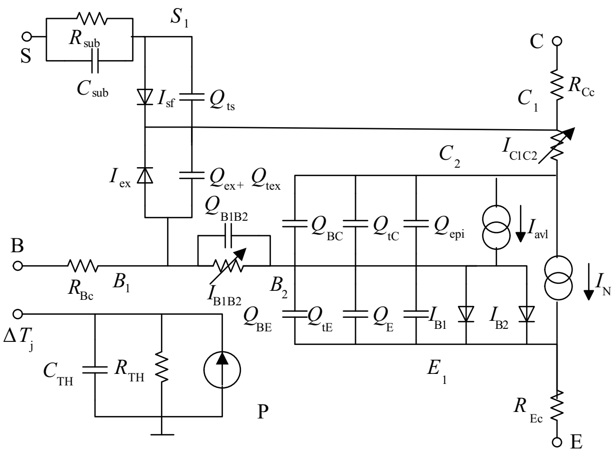

Fig. 1. Proposed large-signal equivalent circuit model.

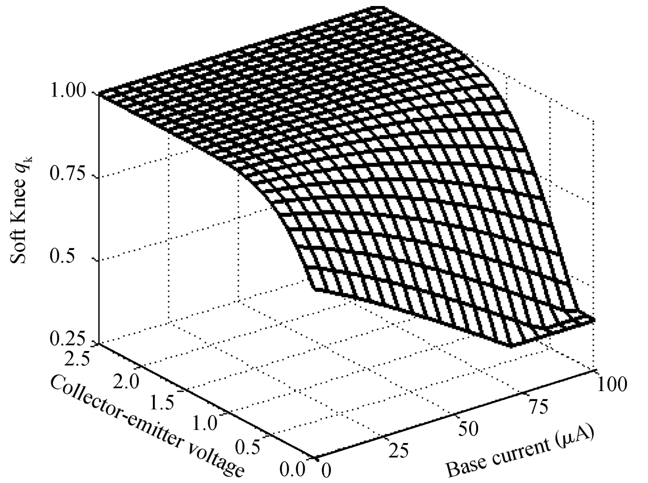

Fig. 2. Value of q_k as a function of the collector–emitter voltage and base current.

(2) The non-ideal reverse current I_{B3}, which originates from the recombination in the depleted base–collector region, has also been eliminated in the proposed model.

(3) The substrate current is partitioned over the constant base resistance when EXMOD = 1[4], and the high injection substrate current I_{sub} has been eliminated. The reverse behavior of the parasitic PNP is not modeled. The current with substrate bias in the forward direction is only included as a signal to the designer as the current with substrate is always in reverse bias[4], then the substrate current in the forward direction can be written as follows:

$$I_{sf} = I_{ST}(e^{v_{SC_1}/V_T} - 1). \quad (3)$$

Note that in this expression I_{ST} is used instead of I_{SsT}, which simplifies parameter extraction, then the parameters I_{SsT} and I_{ksT} have been eliminated in the proposed model.

(4) The overlap capacitances C_{BEO} and C_{BCO} are not included in this model. There is only XC_{JC}, which may be determined from geometrical scaling rules, and the other scaling parameters are eliminated in the proposed model.

(5) The substrate elements which may have an influence on the transistor output characteristics have been included in the proposed model.

(6) The soft knee effect has been taken into account.

The Gummel–Poon model relies on the principle of reciprocity that electrons injected from the emitter into the base will behave essentially the same as those injected from the collector. However, it may not be the case in HBTs in which the emitter and possibly the collector may have a different bandgap than the base. A spike at a wide-bandgap collector can block carriers exiting the base, thus causing the soft knee effect, in which the transistor enters saturation at a higher collector voltage[8]. In the Agilent HBT model, q_{3mod}, which is an empirical function, is used to model the drop in current gain at high currents and low collector voltages which results in a softening of the knee behavior of the common–emitter I–V plot. In the proposed model, q_k is used to represent the soft knee effect, and $q_{k1}, q_{k2}, q_{k3}, q_{k4}, q_{k5}$ and X_{qk1} are the new model parameters. X_{qk1} is the temperature exponent for q_{k1}. The expression for the soft knee effect is shown here:

$$tN = \frac{T_{globalambient} + DTA + (\Delta T)_{dynamicheating}}{T_{globalambient} + DTA}, \quad (4)$$

$$q_{k1\_T} = q_{k1}(tN)^{X_{qk1}}, \quad (5)$$

$$q_3 = e^{q_{k3}V_{ce}}, \quad (6)$$

$$q_4 = e^{q_{k4}I_B}, \quad (7)$$

$$\text{crit} = \frac{q_3}{q_4}, \quad (8)$$

$$q_{kt} = q_{k1\_T}\tanh[(q_{k2} \times \text{crit}) + q_{k5}], \quad (9)$$

if ($q_{kt} < 0.4$)
begin $q_k = 0.4$;
end
else
begin $q_k = q_{kt}$;
end.

V_{ce} is the collector–emitter voltage and I_B is the base current. If the value of q_k is too small, the value of the base current shown in Eqs. (1) and (15) will become larger than the truth value. Thus if the case is used to limit the minimum value of q_k, the value of q_k as a function of the collector–emitter voltage and base current is shown in Fig. 2, and q_k keeps a value of 1 when its effect is not present. Then the main current is written as follows:

$$I_N = \frac{I_f q_k - I_r}{q_B^I}, \quad (10)$$

where the ideal forward current is:

$$I_f = I_{sT}e^{v_{B2E1}/V_T}. \quad (11)$$

The ideal reverse current is:

$$I_r = I_{sT}e^{V_{B2C2}^*/V_T}, \quad (12)$$

Table 1. Parameters for the soft knee effect.

Parameter	q_{k1}	q_{k2}	q_{k3}	q_{k4}	q_{k5}	X_{qk1}
Value	1	1.72	0.76	5550	–0.78	0
Unit	–	–	V^{-1}	A^{-1}	–	–

$$q_B^I = \frac{q_0^I + \sqrt{(q_0^I)^2 + 0.01}}{2}(1 + 0.5n_0 + 0.5n_B), \quad (13)$$

where

$$q_0^I = 1 + \frac{V_{tE}}{V_{erT}} + \frac{V_{tC}}{V_{efT}}. \quad (14)$$

The ideal forward base current has been shown in Eq. (1). The non-ideal forward base current, which originates from the recombination in the depleted base–emitter region and from many surface effects, can be written as:

$$I_{B_2} = \left[I_{BfT}\left(e^{v_{B_2E_1}/m_{Lf}V_T} - 1\right) + G_{min}v_{B_2E_1}\right]/q_k. \quad (15)$$

The proposed model keeps the main features of the MEXTRAM 504 model, such as weak avalanche effects in the collector–base junction, charge storage effects, and velocity saturation effects on the resistance of the epilayer.

3. Parameter extraction and model verification

In order to validate and access the proposed model, we present the extracted model elements for a 0.35-μm SiGe-BiCMOS HBT with a 1×8 μm^2 emitter area. The S-parameter measurements for model extraction and verification were made up from 50 MHz to 20.0 GHz by using an Agilent E8363B network analyzer.

3.1. Parameter extraction

The first step in the determination of parameters is to generate the initial parameter value. The epilayer parameters can be calculated when knowing the emitter dimensions, the thickness and the doping level of the epilayer. The scaling parameter XC_{JC} can be extracted to describe the increase in collector current with collector voltage from the measured data for forward early effect[9], thus it is possible to extract all the proposed model parameters from one measured transistor.

The junction capacitance parameters can be extracted from the measured data for depletion capacitance (CV). The DC characteristics parameters can be extracted from the measurements for terminal voltages versus currents (DC Gummel plots). The additional parameters for the soft knee effect can be determined by fitting the DC output characteristics of the device. The transit time parameters can be determined by fitting the cut-off frequency f_T, which can be obtained from S-parameter measurements in the common emitter configuration[9]. In order to determine the parameters of the temperature scaling rules, part of the measurements have to be repeated at another temperature.

When all of the parameters have been determined, the measured and simulated DC characterization and S-parameter curves may not fit very well, thus it is necessary to use optimization technology to reduce the error between the measured and modeled data. The values of the parameters for the soft knee effect are shown in Table 1. The values of the other parameters are shown in Table 2.

Table 2. Other parameters.

Parameter	Value	Parameter	Value
I_s	3.48×10^{-17} A	C_{jE}	3.65×10^{-17} F
I_k	0.07 A	V_{dE}	0.67 V
V_{ef}	120 V	C_{jC}	4.98×10^{-14} F
V_{er}	2.10 V	V_{dc}	0.69 V
β_f	235	τ_E	7.01×10^{-15} s
I_{Bf}	2.70×10^{-15} A	τ_B	4.20×10^{-13} s
M_{Lf}	2.20	τ_{epi}	2.05×10^{-12} s
β_{ri}	10.50	τ_R	5.19×10^{-10} s
R_E	2.50 Ω	V_{gB}	0.67 V
R_{Bc}	24.70 Ω	V_{gC}	1.08 V
R_{Bv}	46 Ω	V_{gj}	1.07 V
R_{Cc}	29.80 Ω	C_{jS}	7.50×10^{-14} F
R_{Cv}	90 Ω	V_{dS}	0.18 V

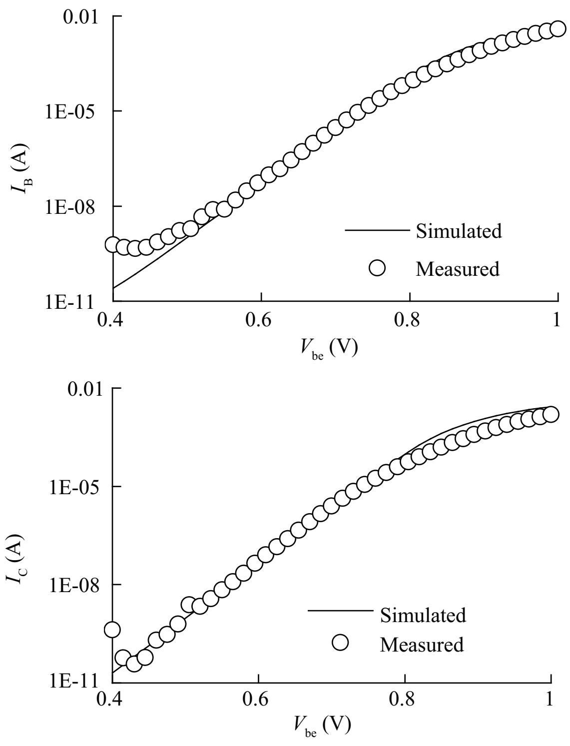

Fig. 3. Forward Gummel plot at V_{BC} = 0 V.

3.2. Model verification

The measured and simulated forward gummel plots are shown in Fig. 3. DC characteristics of the device are compared in Figs. 4 and 5.

Figure 4 shows the collector current and characteristics versus collector–emitter voltage at different forced base currents at room temperature. Figure 5 shows the base–emitter voltage versus collector–emitter voltage at different forced base currents at room temperature. Table 3 shows the average relative errors between the simulated and measured DC characteristics for the proposed and MEXTRAM models. It is obvious that the fit between the measurement and simulation becomes more accurate when the soft knee effect is included in the proposed

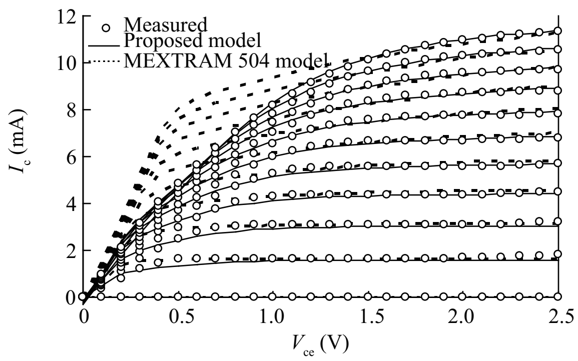

Fig. 4. Collector current I_C as a function of collector–emitter voltage V_{ce} with forced base current. (I_B: 0–100 μA, Step: 10 μA. Circle: Measured data; Solid line: Proposed model; Dot: MEXTRAM 504 model.)

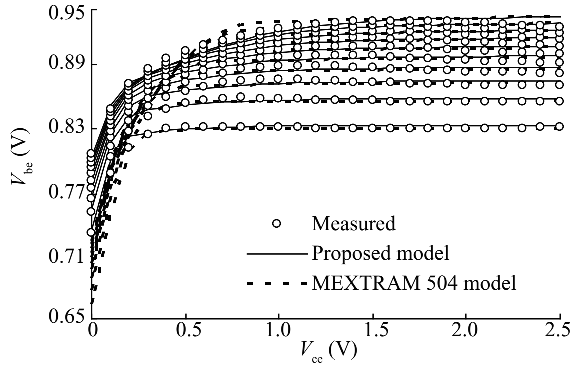

Fig. 5. Base–emitter V_{be} as a function of collector–emitter voltage V_{ce} with forced base current. (I_B: 10–100 μA, Step: 10 μA. Circle: Measured data; Solid line: Proposed model; Dot: MEXTRAM 504 model.)

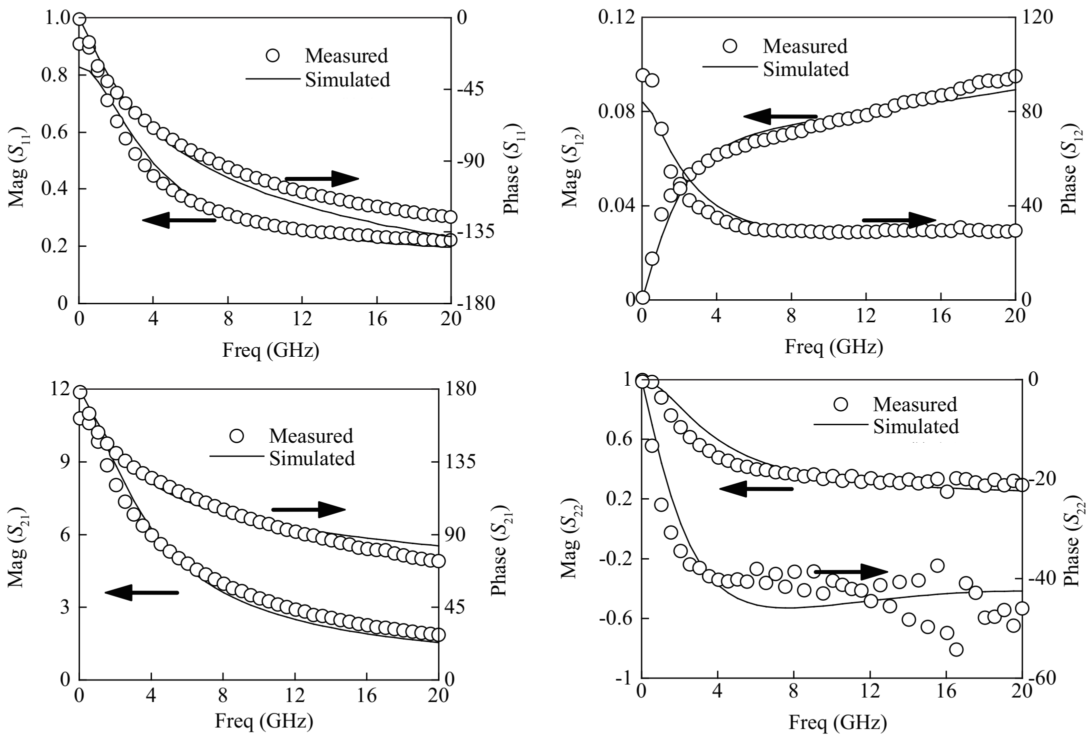

Fig. 6. Comparison of simulated and measured S parameters for the SiGe HBT. (I_B = 70 μA, V_{ce} = 2 V. Circle: Measured data; Solid line: Simulated data.)

Table 3. Relative errors between the simulated and measured DC characteristics.

Parameter	I_C	V_{be}
MEXTRAM model	9.8%	5.4%
Proposed model	3.5%	3.8%

model.

In order to verify the AC behavior, the proposed model is validated by comparing the measured and simulated S parameters. Figures 6–8 compare the measured and simulated S-parameters for the SiGe HBT in the frequency range of 50 MHz to 20 GHz under different bias conditions. A good agreement over the whole frequency range is obtained.

4. Conclusion

In this paper, an improved large-signal equivalent-circuit model for SiGe HBTs based on the MEXTRAM model (level 504.5) is proposed. Most of scaling parameters are eliminated in the proposed model, thus model parameter determination from the signal geometry transistor becomes convenient compared to the MEXTRAM 504 model. The excellent agreement of the measured and modeled results for DC and S-parameters (from 50 MHz to 20 GHz) shows that the proposed model is accurate and reliable. The source-code of the proposed model, which is developed using Verilog-A, has been compiled and linked to the Agilent ADS2008 and implemented using the circuit simulator/hpeesofsim.

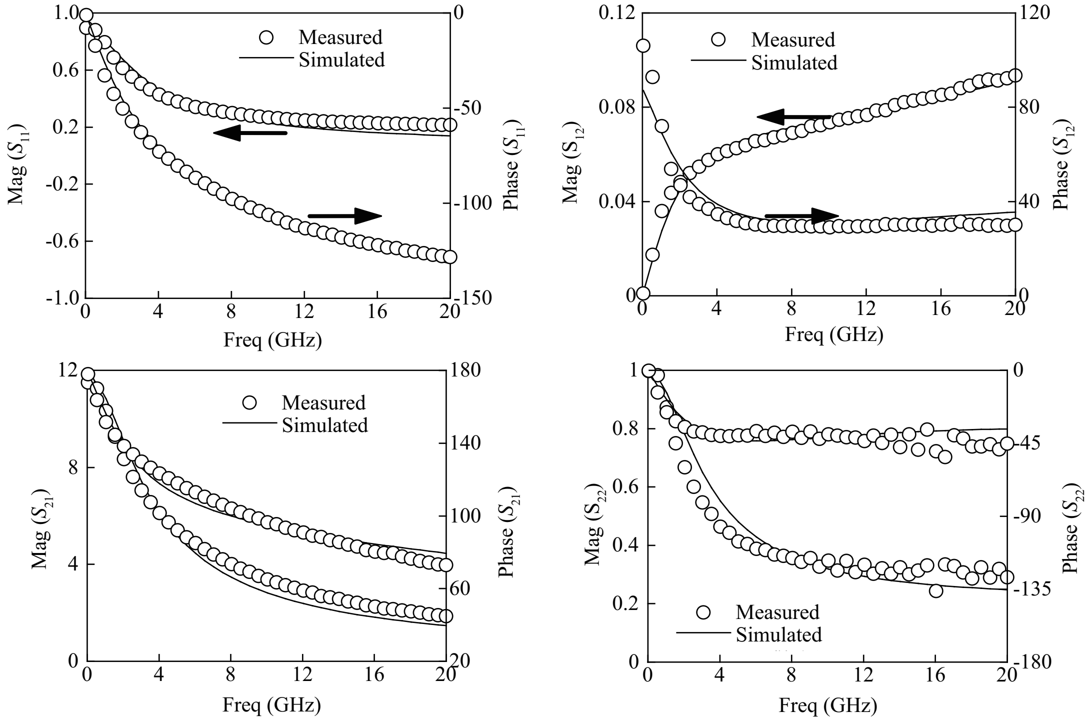

Fig. 7. Comparison of simulated and measured S parameters for the SiGe HBT. (I_B = 50 μA, V_{ce}= 2 V. Circle: Measured data; Solid line: Simulated data.)

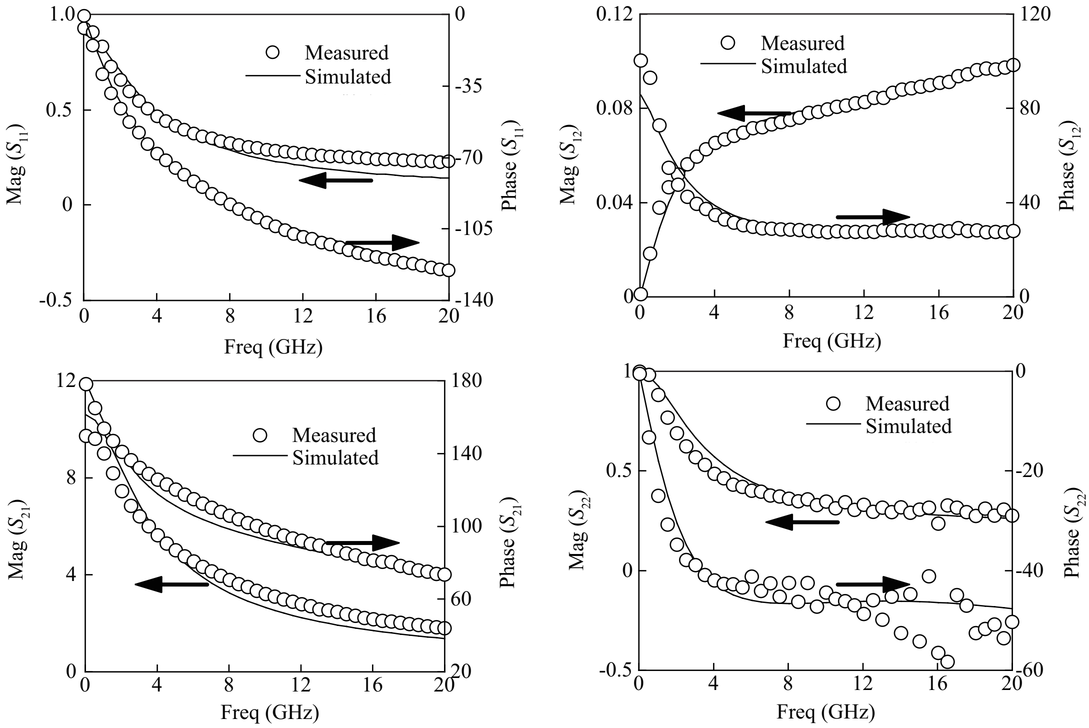

Fig. 8. Comparison of simulated and measured S parameters for the SiGe HBT. (I_B = 40 μA, V_{ce} = 1.5 V. Circle: Measured data; Solid line: Simulated data.)

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