Substrate Effects in SiGe HBT Modeling

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***Abstract*— This paper reports on a direct parameter extraction method for SiGe Heterojunction Bipolar Transistors (HBT's). Unlike previous reported direct parameter extraction methods the method presented here can be used to determined the elements associated with the parasitic substrate transistor action. The method is experimentally verified on a 0.8μm 35 GHz f_T SiGe HBT in the frequency range from 45 MHz-26.5 GHz.**

I. INTRODUCTION

SiGe HBT technology seems to be well suited for implementing critical subsystems in Synthetic Aperture Radar (SAR) systems performing e.g. quadrature modulation and demodulation of wideband linear-FM modulated signals around microwave carriers [1]. However investigation using a 0.8μm 35 GHz f_T SiGe HBT process have shown a poor correlation between predicted frequency response from simulations and what is actually measured on the SiGe HBT devices. It is found that this is caused by improper modeling of the parasitics around the intrinsic SiGe HBT device. Improved modeling of parasitics associated with the individual transistors is a prequisite to achieve wideband operation in advanced SiGe HBT MMIC's for SAR applications.

As the frequency of operation increases the influence from parasitic substrate effects becomes more important and must be accurately accounted for in the modeling of the SiGe HBTs. Existing methods for substrate parasitic extraction relies on either numerical optimization techniques [2], or cumbersome numerical simulation with requirement on process information often not available [3]. It is well-known that numerical optimization techniques may lead to extracted elements values which depends on the starting value and may be non-physical [4]. Thus in recent years a trend toward direct parameter extraction methods for the small-signal equivalent circuit of bipolar devices have been observed [4]-[8]. Most of these paper have been concerned with parameter extraction for GaAs HBTs where the substrate have no direct effect on the performance. Direct parameter extraction methods have been reported for Si BJT [5] and SiGe HBTs [8] however substrate effects where not taken into account in these methods.

In this work a direct parameter extraction method for SiGe HBTs is described. Unlike previous reported extraction methods the method presented here can be used to determine the elements associated with the parasitic transistor action. The method uses a multi-step deembedding approach and requires knowledge of the measured S-parameters for the SiGe HBT biased in forward active, cut-off and saturated regions. The applicability of the direct parameter extraction method in connection with large-signal model parameter extraction is illustrated. The direct parameter extraction procedure is experimentally verified in the frequency range from 45 MHz-26.5 GHz using a 0.8μm 35 GHz f_T SiGe HBT device with an emitter area of $2x6x0.8\mu m^2$.

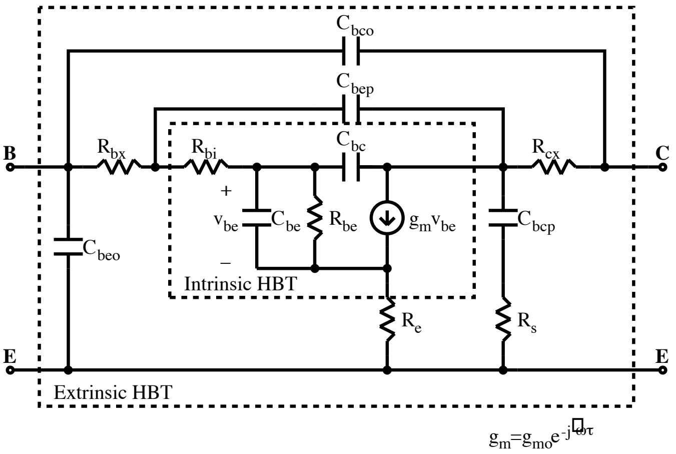

Fig. 1. High-frequency equivalent circuit model for a double-poly SiGe HBT device in the forward active region.

II. DIRECT PARAMETER EXTRACTION METHOD FOR SIGE HBT EQUIVALENT CIRCUIT

Small-signal equivalent circuit models for SiGe HBT devices can naturaly be divided into an intrinsic part describing the transistor action in a vertical structure underneath the emitter and an extrinsic part due to unavoidable parasitics associated with the device structure as seen in Fig.1. The intrinsic part is described with the well-known hybrid-π equivalent circuit which follows from a linearization of the Gummel-Poon large-signal model in the forward active region. The transconductance g_m contains a delay component τ in order to model the excess phase shift which becomes noticeable at frequencies approching f_T. The base-emitter capacitance C_{be} contains both depletion and diffusion components while the base-collector capacitance C_{bc} only includes the depletion components. The intrinsic base resistance R_{bi} model the current dependent part of the total base resistance arising due to conductivity modulation of the internal base sheet resistance. The reduced base-width modulation (The Early effect) experienced in SiGe HBTs means that the output conductance g_o can be neglected. As shown in Fig. 1 the parasitics in the extrinsic part includes fixed base, collector and emitter access resistances and parasitics due to substrate transistor action C_{bep}, C_{bcp} and R_s. Furthermore in modern double-poly SiGe HBT devices a large part of the total capacitance between base-emitter and base-collector terminals is due to fixed oxide capacitances shown in Fig. 1 as C_{beo} and C_{bco} respectively. The small-signal equivalent circuit model seen in Fig. 1 should be able to accurate describe the behavior for a SiGe HBT from DC to frequencies in excess of the f_T for the devices.

A. Fixed Access Resistances and Fixed Oxide Capacitances

In the cut-off mode the small-signal equivalent circuit for a SiGe HBT consist only of capacitances and resistances. In the lower frequency range where the effects of the resistors remains negligible the resulting capacitance network have a π-topology and the total input capacitance C_{in} consisting of the fixed oxide capacitance C_{beo} and voltage dependent base-emitter depletion capacitance C_{be} can be found as [9]

$$\omega C_{in} = Imag(Y_{11} + Y_{12}) \tag{1}$$

where Y_{11} and Y_{12} are measured Y-parameters de-embedded from pad and interconnect line parasitics. Similar the feedback capacitance C_{fb} which consist of the fixed oxide capacitance C_{bco} and the total voltage dependent base-collector depletion capacitance $C_{bc} + C_{bep}$ can be found as

$$\omega C_{fb} = Imag(-Y_{12}). \tag{2}$$

The extraction of the fixed oxide capacitances are accomblished by fitting non-linear expressions to measured C_{in} and C_{fb} over reverse and slightly forward biased junctions as seen in Fig. 2.

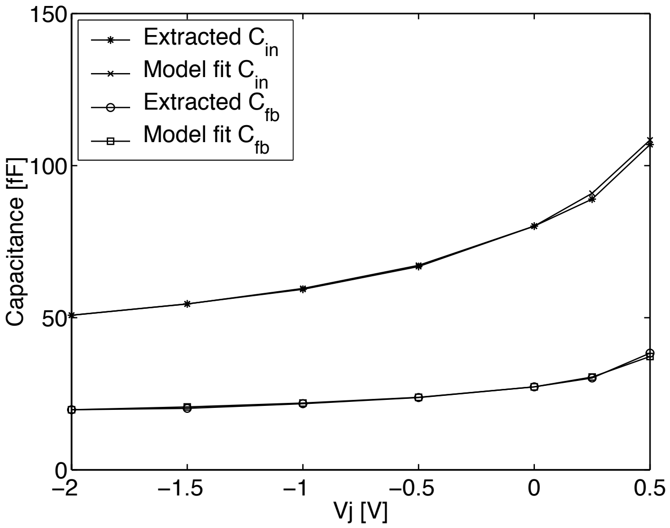

Fig. 2. Model fit for total input capacitance and feedback capacitance for a SiGe HBT device using extracted values for fixed oxide capacitances and voltage dependent parameters for the junctions.

It have been shown that a HBT biased in saturation (V_{ce}=0.0V, I_c $\approx$0A) and driven with a very large forward base current I_b can be represented with a simple T-equivalent circuit model consisting only of external base, emitter and collector series resistances [9] because the dynamic resistances of all junctions decreases toward zero. At very high base currents the base, emitter and collector resistances are then given by the equations

$$R_{bx} = Real(Z_{11} - Z_{12}) \tag{3}$$
$$R_e = Real(Z_{12}) \tag{4}$$
$$R_{cx} = Real(Z_{22} - Z_{12}) \tag{5}$$

where Z_{11}, Z_{12} and Z_{22} are measured Z-parameters de-embedded for pad and interconnect line parasitics for the SiGe HBT biased in the saturation region. The extraction of the fixed base, emitter and collector resistances are based on the extrapolation of the plots of the real part of the Z-parameters versus $1/I_b$ up to the ordinate as illustrated in Fig. 3. A significant part of the applied base current in SiGe HBTs will flow in the substrate because the parasitic base-emitter junction of the substrate transistor turns on in saturation. Only a very small part of the applied base current will actually flow thru the intrinsic base resistance explaining the slow variation of $Real(Z_{11} - Z_{12})$ with base current as observed in Fig. 3.

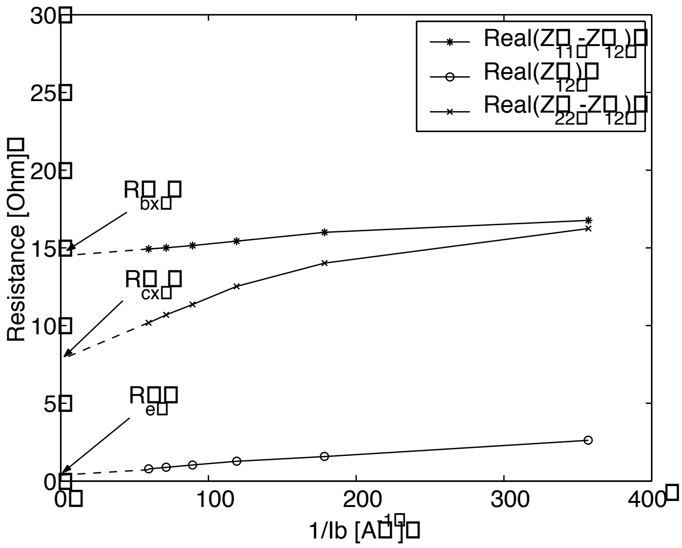

Fig. 3. Extraction of fixed base, collector and emitter series resistances.

B. Substrate Parasitics Extraction

Once the fixed access resistances and fixed oxide capacitances have been extracted it is possible to remove their influence by de-embedding. However it should be noticed that the emitter resistance can not be de-embedded at this point as the parasitic substrate network is connected to the emitter node as seen in Fig. 1. The equivalent circuit model for the SiGe HBT in the cut-off mode after de-embedding can be represented as seen in Fig. 4. Straightforward analysis shows that the Y-parameters Y_{22} and Y_{12} for this equivalent circuit are given by

$$Y_{22} = \frac{j\omega C_{bcp}}{1 + j\omega C_{bcp} R_s} + j\omega C_{bep} + \frac{j\omega C_{bc}(1 + j\omega C_{be} R_{bi})}{1 + j\omega (C_{be} + C_{bc}) R_{bi}} \tag{6}$$

$$Y_{12} = -j\omega C_{bep} - \frac{j\omega C_{bc}}{1 + j\omega (C_{be} + C_{bc}) R_{bi}} \tag{7}$$

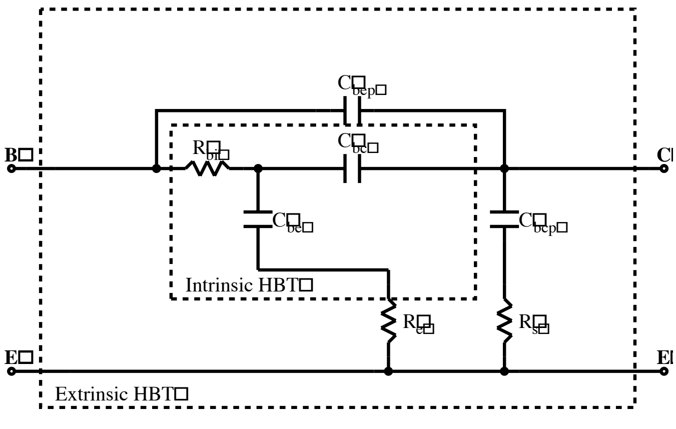

Fig. 4. Small-signal equivalent circuit model for a SiGe HBT biased in the cut-off mode after de-embedding.

where the influence of R_e have been neglected for simplicity. The influence of the parasitic base-emitter capacitance C_{bep} can be removed by adding the two Y-parameters together

$$Y_{22} + Y_{12} \approx \frac{j\omega C_{bcp}}{1 + j\omega C_{bcp} R_s} \tag{8}$$

where the approximation is valid for $\omega^2 C_{bc} C_{be} R_{bi} \approx 0$ which is equivalent to neglecting the internal feedback path thru the device. Thus the substrate resistance R_s and parasitic substrate base-collector capacitance C_{bcp} are extracted as follows

$$R_s = Real\left(\frac{1}{Y_{22} + Y_{12}}\right) \tag{9}$$

$$\omega C_{bcp} = \frac{-1}{Imag\left(\frac{1}{Y_{22}+Y_{12}}\right)}. \tag{10}$$

The frequency dependence of the extracted substrate resistance and parasitic substrate base-collector capacitance for the 2x6x0.8 μm^2 area SiGe HBT is shown in Fig. 5. At low frequencies the extraction of the substrate resistance are inaccurate because the measured Y-parameters are dominated by capacitive effects. At high frequencies the extracted parasitic base-collector capacitance shows a frequency dependence which identify the frequency region where the approximation used in the extraction method becomes inaccurate. The extraction of the substrate parasitics should therefore be confined to the frequency range where the substrate resistance R_s shows flat characteristics and ωC_{bcp} depends linear on the frequency. Extraction over several bias points gives the voltage dependence of the parasitic base-collector capacitance.

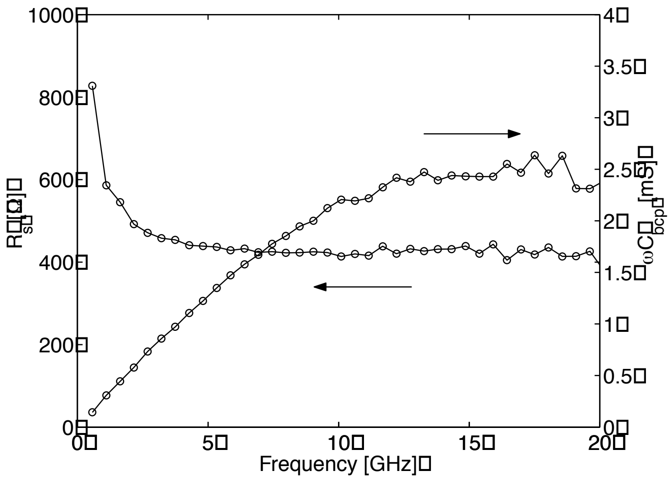

Fig. 5. Frequency dependence of extracted substrate parasitics for a SiGe HBT device biased in the cut-off region.

C. Determination of Intrinsic Hybrid-π Equivalent Circuit

At this point all external elements of the small signal equivalent circuit for the SiGe HBT device have been extracted except the parasitic base-emitter capacitance C_{bep}. It is however possible to extract the elements of the intrinsic hybrid-π equivalent circuit independently of this capacitance [8]. In order to do this the influence from the external elements of the SiGe HBT must first be removed using the following multi-step de-embedding approach: Step 1) de-embed fixed oxide capacitances. Step 2) de-embed fixed base and collector resistances. Step 3) de-embed substrate resistance and parasitic base-collector capacitance (bias-dependent). Step 4) de-embed fixed emitter resistance. Once all the intrinsic elements have been determined the parasitic base-emitter capacitance is found using the value for the total base-collector depletion capacitance extracted previously.

The frequency dependence of the intrinsic base resistance R_{bi} extracted for the 2x6x0.8 μm^2 SiGe HBT biased in the forward active region is shown in Fig. 6. The observed weak frequency dependence of the extracted intrinsic base resistance illustrates the robustness of the extraction method.

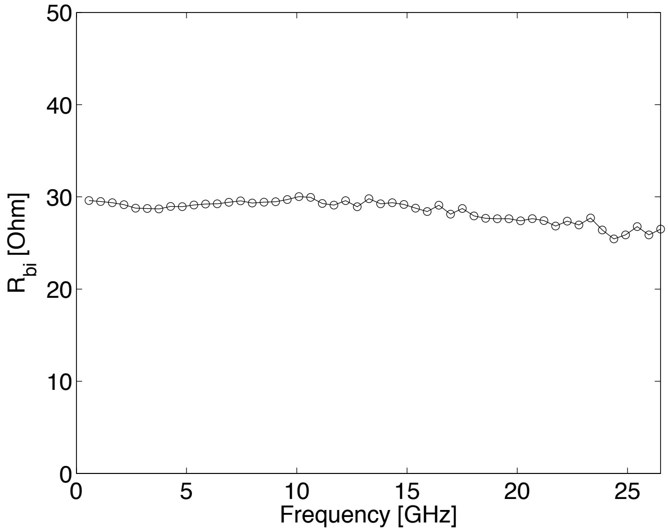

Fig. 6. Frequency dependence of extracted intrinsic base resistance for a SiGe HBT biased in the forward active region.

III. APPLICABILITY FOR LARGE-SIGNAL MODELING

Though an accurate extraction method for the small-signal equivalent circuit of SiGe HBT devices is certainly important, most circuit design requires a large signal model such as the VBIC95 model [10]. The applicability of the direct parameter extraction method in connection with extraction of the VBIC95 model parameters of interest for ac-modeling will be illustrated next.

The bias dependence of the intrinsic base resistance arising due to conductivity modulation can according with the VBIC95 model be represented as R_{bi}/q_b, where q_b is the normalized base charge [10]. Extraction at several bias points in the forward active region is used to determined the intrinsic base resistance. As the collector current I_c goes toward zero, the normalized base charge approches unity. The extraction of the VBIC95 model parameter R_{bi} is then achieved by extrapolating extracted values of R_{bi}/q_b versus collector current I_c onto the ordinate axis, as shown in Fig. 7.

In the direct parameter extraction method, the excess phase delay is modeled as a phase shift affecting the small-signal transconductance as $g_{mo}e^{-j\omega\tau}$. An estimate for the excess phase delay VBIC95 model parameter T_d can be estimated from extracted values of τ versus collector current I_c as shown in Fig. 8. At low bias currents, the excess phase delay decreases slowly with the increase in collector current, but once base-widening effects becomes noticeable it increases due to the increase in the forward transit time. In the VBIC95 model, the excess phase delay is bias independent so the

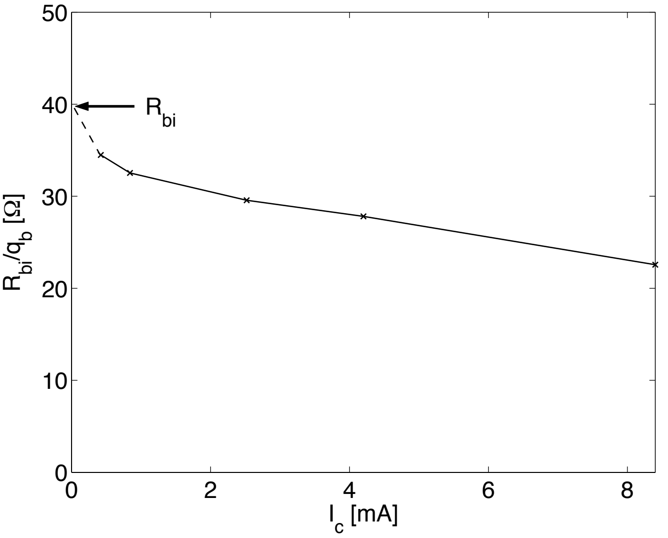

Fig. 7. Extracted bias dependence for intrinsic base resistance for the SiGe HBT biased in forward active region.

extracted value at low bias current should be used for T_d.

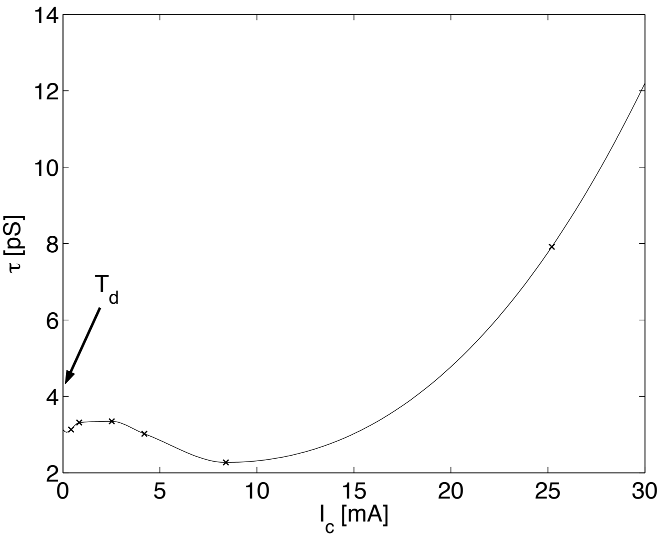

Fig. 8. Extracted bias dependence for excess phase delay for the SiGe HBT biased in forward active region.

IV. Experimental Result

The direct parameter extraction method have been verified on measured S-parameters for the $2x6x0.8\mu m^2$ area SiGe HBT device in the frequency range from 45 MHz-26.5 GHz. Pad and interconnect line parasitics have been carefully de-embedded from the measurement results. Fig. 9 shows the excellent agreement between measured and modeled S-parameters for the bias point (V_{ce}=1.5V, I_c=4.2mA) corresponding to peak f_T for the device.

V. Conclusions

A direct parameter extraction method well-suited for modern double-poly SiGe HBT devices have been presented. The method includes the effect associated with the parasitic substrate transistor as well as fixed oxide capacitances and

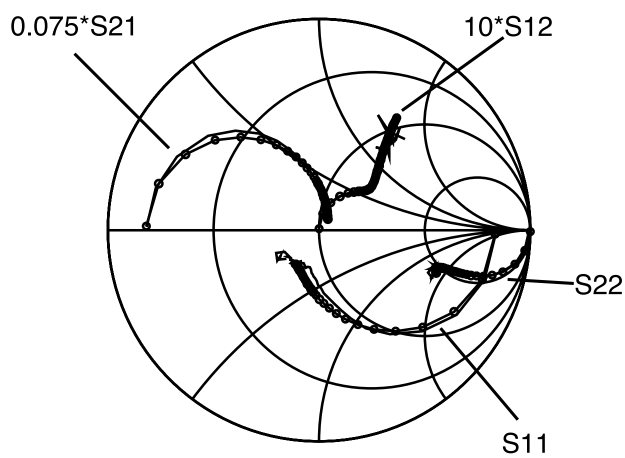

Fig. 9. Measured (-) and modeled (-o-) S-parameters for the $2x6x0.8\mu m^2$ area SiGe HBT device biased in the forward active region (45 MHz-26.5 GHz,V_{ce}=1.5V, I_c=4.2mA).

have been experimentally verified in the frequency range from 45 MHz-26.5 GHz.

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References

[1] E. Linzt Christensen (ed), *SAR++ System Design Report*, Technical Report R. 693, Technical University of Denmark, Dept. of Electromagnetic Systems, Jan 2000.

[2] J.Vidkjær, "Substrate Effects in HBT Modelling for RFIC Design," *ECCTD*, 2001.

[3] M. Pfost, H. M. Rein and T. Holzwarth, "Modeling Substrate Effects in the Design of High-Speed Si-Bipolar IC's," *IEEE Jour. Solid-State Circuits*, vol. 31, no.10, pp. 1493–1501, Oct. 1996.

[4] D. Costa, W. U. Liu and J. S. Harris, "Direct Extraction of the AlGaAs/GaAs Heterojunction Bipolar Transistor Small-Signal Equivalent Circuit," *IEEE Trans. Electron Devices*, vol. 38, no.9, pp. 2018–2024, sept. 1991.

[5] S. Lee, B.R. Ryum and S.W. Kang, "A New Parameter Extraction Technique for Small-Signal Equivalent Circuit of Polysilicon Emitter Bipolar Transistors," *IEEE Trans. Electron Devices*, vol. 41, no.2, pp. 233–238, Feb. 1994.

[6] Y. Suh et al, "Direct Extraction Method for Internal Equivalent Circuit Parameters of HBT Small-Signal Hybrid-Π Model," *IEEE MTT-S Digest*, 2000, pp. 1401–1404.

[7] E. Wasige et al, "An analytic expression for the HBT extrinsic base-collectorcapacitance derived from S-parameter measurements," *IEEE MITT-S Digest*, 2002, pp. 733–736.

[8] B.S. Kim et al, "Analytic determination of hybrid π equivalent circuit parameters of SiGe HBTs using admittance equations," *Asia-Pacific Microwave Conference*, November 2002, pp. 466–469.

[9] Y. Gobert, P.J, Tasker and K.H. Bachem, "A Physical, Yet Simple, Small-Signal Equivalent Circuit for the Heterojunction Bipolar Transistor," *IEEE Trans. Microwave Theory and Techniques*, vol. 45, no.1, pp. 149–153, Jan. 1997.

[10] C. C. McAndrew et al, "VBIC95, The Vertical Bipolar Inter-Company Model," *IEEE Jour. Solid-State Circuits*, vol. 31, no.10, pp. 1476–1483, Oct. 1996.